Tasmanian Organic Soils

by

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Abstract

The character, extent and location of Tasmanian organic soils have been largely overlooked in Australian soil classification and taxonomy, with only a loose interpretation of northern hemisphere organic soil classifications applied. The aim of present work is to produce a classification of the organic soils, based on measurable soil properties and to then relate the characteristic organic soil properties to environmental factors. The relationship between organic soil characteristics and environmental factors will enable predictive mapping of the occurrence and organic content of organic soils in Tasmania. Tasmanian organic soils were sampled across 127 sites yielding a total of 1159 soil pits. Soil and environmental characteristics were recorded for each soil pit. Unsupervised clustering of the soil characteristics from each soil pit distinguished 23 organic soil groups. A classification key for identifying the 23 clusters was produced using the soil characteristics, soil organic carbon, humification, soil total nitrogen and organic soil depth. Dominant environmental factors influencing the 23 clusters were found, through vector analysis, smooth plate spline contouring and multinomial log-linear modelling to be: vegetation, burn frequency, topography, geology, altitude and climate. In order to predict the location and occurrence of the soils and soil characteristics produced through unsupervised clustering, the dominant environmental factors were subsequently used to provide cluster centroids for a supervised clustering. The resulting 41 soil groups were found to be distinguishable in terms of vegetation type, geology, topography and microtopography. The supervised clusters were found to perform better than the available vegetation classifications in predicting the unsupervised clusters. Organic soil carbon, bulk density and depth were used to model organic soil carbon stocks in Tasmania and provide a geographic context for the supervised and unsupervised soil clusters. Stepwise regression of soil organic carbon, showed slope as the dominant predictor across organic soil producing vegetation types. The regression models allowed for mapping of organic soil areal extent and soil organic carbon stocks in Tasmania, producing a value of 3,072 Tg of soil organic carbon over 8, 974 km^2.

Suggested changes to the Australian Soil Classification for the order organosol include the addition of folic, lignic, arenic and argyllic to the differentiae. Suggested

family criteria include: humification of surface tiers, organic horizon thickness, botanical composition of surface layers, botanical composition of dominant layers and acidity classes below pH_{CA} 4.6. Changes to landform labels are also suggested.

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Chapter 1

Introduction

1.1 Definition of organic soils

Organic soil is an accumulation of organic detritus which usually has a minimum depth and percent organic carbon as part of its definition. Taxonomies differ in the acceptable depth and amount of organic carbon necessary for a soil to qualify as organic. The term organic soil used in this thesis follows the definition of Soil Taxonomy (Soil Survey Staff 2006) and the Australian Soil Classification (Isbell 2002) and is as follows,

Soils that are not regularly inundated by saline tidal waters and either:

Have more than 0.4 m of organic materials within the upper 0.8 m. The required thickness may either extend down from the surface or be taken cumulatively within the upper 0.8 m; or

Have organic materials extending from the surface horizon to a minimum depth of 0.1 m; these either directly overlie rock or other hard layers, partially weathered or decomposed rock or saprolite, or overlie fragmental material such as gravel, cobbles or stones in which the interstices are filled or partially filled with organic material. In some soils there may be layers of humose and/or melacic horizon material underlying the organic materials and overlying the substrate.

Organic materials are defined as plant-derived organic accumulations that are either:
a) saturated with water for long periods or are artificially drained and, excluding live plant tissue, i) have 18% or more organic carbon if the mineral faction is 60% or more clay, ii) have 12% or more organic carbon if the mineral fraction has no clay or iii) have a proportional content of organic carbon between 12 and 18% if the clay content of the mineral fraction is between zero and 60%; or b) saturated with water for no more than a few days and have 20% or more organic carbon.

Other definitions are reviewed in chapter 2. The terms peat, peatland, mire and bog have been used extensively in the literature and are also reviewed in chapter 2.

1.2 Importance of organic soils

The amount of organic carbon in soil is estimated globally at 1200-1500 Pg in the top 1 metre (Post *et al.* 1990, Batjes 1996), which constitutes the second largest carbon pool after the oceans. Soils dominated by organic matter are therefore important carbon pools, as well as being recognised for their role in providing a vital natural resource as an important ecosystem for a wide range of wildlife (Joosten and Clarke 2002). The International Mire Conservation Group (IMCG) considers that peatlands are important in supporting biological diversity and species at risk, maintaining freshwater quality and hydrological integrity, storing and sequestering carbon, as well as containing geochemical and palaeo archives (Joosten and Clark 2002). Furthermore, peatlands have social, cultural and economic values (Joosten and Clark 2002). Organic soils are an important component of many Tasmanian ecosystems. The terms peat, peatland (Hannan *et al.* 1993, Whinam and Hope 2005) and blanket bogs (Jarman *et al.* 1988a, Pemberton 1989, Hannan *et al.*1993, Whinam and Hope 2005) have been used to describe a subset of organic soils, which are found predominantly in the reserved parts of the west and southwest of the state. A large section of this area is a world heritage area. Tasmanian peatlands meet the natural criteria for listing of the Tasmanian Wilderness World Heritage Area. Peatlands and landscapes with organic soils in Tasmania are: outstanding examples representing the major stages of the earth's evolutionary history; outstanding examples representing significant ongoing geological processes, biological evolution and man's interaction with the environment; superlative natural phenomenon, formations or features; and, significant habitats where threatened species of plants and animals of outstanding universal value from the point of view of science and conservation still survive (DPWH 1992).

1.3 Organic soil classification

Classification is an important and useful tool for communicating variation in soils. A classification of soils will aim to group together soils with similar properties. These classificatory units can be applied more widely than the samples from which they were derived. Classification therefore serves as a predictive tool.

Classifications of organic-rich materials can be found within soil, landform and vegetation classification systems and have been produced at local to international levels of application. Soil classification and landform classifications are the most widely used systems. National systems usually attempt to both inform and incorporate international systems. Soil classification systems usually classify using measurable and observable soil properties which have been shown to relate to pedogenesis. Landform classifications of organic materials have been developed regionally and have yet to produce an all-encompassing, internationally applicable classification system, but are nevertheless considered in this thesis and reviewed in chapter 2. Although the Australian Soil Classification (Isbell 2002) is used for classifying Australian soils, the organic soil order, organosol, is poorly-represented (Isbell 2002). Landforms incorporating organic deposits are poorly-understood in Tasmania, although *Sphagnum*-dominated systems have been quantitatively classified on the basis of their floristics (Whinam *et al.* 1989, Whinam 1995, Whinam *et al.* 2001). Isbell (2002) stated that a strong sense of purpose in terms of land use and management should form the basis of the Australian Soil Classification. The areas in Tasmania where organosols are found are predominantly in conservation reserves, such as national parks, world heritage areas and regional reserves. Low productivity Forestry Tasmania sites beyond the periphery of the World Heritage Area also have some organosols under rainforest, rainforest scrub and *Melaleuca ericifolia* scrub. The waters from the world heritage area are used for hydro-electricity production. The main uses or organosols are therefore nature and water conservation, with limited areas in state forest used for timber production.

1.4 How have Tasmanian organic soils been classified?

The definitions of organic soil, organic material and peat have changed in Australia since the first national classification systems. What was considered organic soil, organic material or peat in the past, may no longer qualify as such under the present national and international taxonomic definitions.

The first mention of peat in an Australian soil classification system appears in 1931 when Prescott classified high moor and mountain soils as a major soil group of Australia. This group was described as profiles with peat over clay or skeletal soils over rock. There was no more detail on the nature of peat and they were not defined. Local soil maps and reports mention peats at Mowbray Swamp in the north west of the State (Hubble 1951, 1956) and peats on the Central Plateau (Nicolls 1959), although no description of peat is given. Nicolls (1957) describes buttongrass peats in a local survey in the north west of the State with surface organic carbon contents and horizon depths provided to depths of 8 - 15 cm. The organic carbon contents in the surface horizon just meet with the present definition of organic matter in 6 out of 8 of the soil profiles, but no organic carbon content is given for the remaining 40 to 85 cm of the profiles, only the comment that organic content decreases with depth. For two buttongrass peat profiles, organic carbon contents were provided for each horizon to depth. These profiles would not qualify as organosols under the present definition (Isbell 2002). It is therefore unlikely that the rest of the buttongrass peats described by Nicolls (1959) would be defined as organosols under the present definition (Isbell 2002).

No further divisions in Australian organic soil classification were given until Stephens (1962), who classed organic soils as solum dominated by acid peat or a peaty eluvial horizon and differentiated the great soil groups: skeletal soil, moor peats, moor podzol peats, alpine humus soils and acid swamp soils. Skeletal soils, under Stephens' classification (1962) were nascent soils in that they were stony or gravelly, showing no profile development other than organic matter accumulation in the surface. Moor peats were described as having little horizon development, with the greater part of the profile consisting predominantly of organic matter, black or nearly black in colour, and generally at or near saturation with water. Alpine humus soils are described as peaty loams with an accumulation of organic matter in the surface horizon. Moor podzol peats are described as ground water podzols with a fibrous peat accumulation on the surface. Peat is referred to as an A0 horizon development under restricted drainage, with the water table frequently at the surface. The moor podzol peats are described as having siliceous, organic matter-stained A1 and A2 horizon, a hard-pan B1 horizon, and variable B2 and C horizons. Acid swamp soils are described as containing a variable mixture of organic and mineral material of acid reaction under the influence of a water table that periodically is at, above, or near the surface of the profile. The acid swamp soils are further described as ranging from peaty sands, sandy loams, loams and true peats, with organic content decreasing with depth. Stephens' classification (1962) does not provide definitions of peat or organic matter.

Northcote (1962) produced an atlas of Australian soils which included four mapping units for peat: basin plains (swamps) of neutral to alkaline peaty soils, basin plains (swamps) of acidic peaty soils, swampy plains with sand ridges - swampy plains of peaty soils and their burnt remains, and swampy plains, floodplains and terrace remnants - swampy plains of peaty soils. The only two peat mapping units appearing in Tasmania (Northcote 1962) were three small areas of peat mapped as basin plains (swamps) of acidic peaty soils and basin plains (swamps) of neutral to alkaline peaty soils in the north west corner of Tasmania, near Smithton. The large areas of the Central Plateau, west, west coast and south west of Tasmanian now associated with organic soil development (Isbell 2002) and mapped as containing organosols (Isbell *et al.* 1997) were mapped as predominantly leached sandy soils, dissected with valley plains of acid, peaty soils or yellow leached friable earths with organic peaty soils on plains, beside streams or in narrow valleys. The Central Plateau region is mapped as organic loamy soils with an organic A horizon with a possible association with organic peaty soils on plateau remnants or small valley plains. Northcote's soil map units were delineated on the basis of landscapes and consisted of associations of soils. He, therefore, used air photos and/or geographical, topographical, ecological maps and restricted field inspection or general knowledge to map the associations of soils of the south west, west and central plateau regions of Tasmania (Northcote 1960).

Nicolls and Dimmock (1965) produced an atlas of Tasmanian soils with mapping units that were based on the great soil group classification of Stephens (1962) and included the units: skeletal soils and moor podzol peats, alpine humus soils, alpine humus soils with moor peats and, acid swamp soils and fen soils. Nicolls and Dimmock (1965) mapped the south west of Tasmania as having skeletal soils on slopes with moor podzol peats on valley plains and lower slopes, the upper Central Plateau as having alpine humus soils with moor peats in marshy situations, the lower Central Plateau as having alpine humus soils and 3 small areas of acid swamp and fen soils in the north west of Tasmania in areas of former swamp. In the production of the map, no soil surveys were conducted in the Central Plateau, the south west or west of Tasmania, with the exception of a small area around Strahan in the west, and interpretation was deduced from geological maps (Nicolls and Dimmock 1965). Frequent observations were made in the outer Central Plateau and sparse observations in the inner Central Plateau, west and south west of the State.

Stace *et al.* (1968) included four great soil groups in their grouping of soils dominated by organic matter: alpine humus soils, humic gleys, acid peats, and neutral and alkaline peats. Organic soils were defined as being dominated by a large quantity of organic matter that has accumulated in the topsoil and which tends to obscure the effect of other components. Alpine humus soils were characterised by a marked accumulation of acidic, well-humified organic matter that is incorporated in to the mineral soil to form a thick surface horizon on profiles otherwise showing little horizon development. The example soil under this great soil group given for Tasmania is from Mount Wellington at 1,091 m a.s.l. on Jurassic dolerite. The sample profile would not, under the present classification system (Isbell 2002), be classed as an organosol due to the shallow horizon of organic material on a largely mineral soil. Humic gleys are described as acid to neutral, predominantly mineral soils with an organic A horizon. The examples provided by Stace *et al.* (1968) would not be classed as organosols under the present classification system (Isbell 2002), with organic carbon contents of the upper A horizon below 12%. Neutral to alkaline peats are described as having an accumulation of organic matter under the influence of alkaline groundwater. No example from Tasmania is given, but descriptions are of black peat which is partly decomposed and mixed with sand. Acid peats are described as having little horizon development with an accumulation, on the surface, of almost black, strongly acid, peaty organic matter which is maintained near saturation with water. The peats are further described as well-decomposed and sticky with fibrous roots near the surface and the lower horizons commonly clayey or gravelly grading to the underlying mineral material. The example profiles provided are from the Central Plateau and Mount Wellington, both on Jurassic dolerite above 1,000 m a.s.l., with only the sample from the Central Plateau meeting the present criteria (Isbell 2002) for an organosol. Organic matter is defined in Stace *et al.* (1968), but no limits are set to the quantity or volume required for an organic soil and the methods used are no longer acceptable as they are considered to overestimate the amount of organic carbon (Heiri *et al.* 2001). It was not until 1971 that organic soils were defined in terms of limits of organic content and depth (Northcote 1971, Northcote *et al.* 1975). Northcote *et al.* (1975) produced a description, accompanied with a map of Australian soils, which included a definition of an organic soil:

> Organic soils have high contents of, or are dominated by, organic matter for at least the top 30 cm of the profile. The organic content to this depth should be 20% or more when the clay content of the fine earth fraction is 15% or less, or 30 % or more when the clay content of the earth is greater than 15%.

Subdivisions of organic soils were on the basis of soil reaction: acid (pH < 6.5), neutral (pH 6.5 - 8.0) and alkaline (pH > 8.0). Northcote's (1975) accompanying soil map showed organic soils only in one small area in the north west of Tasmania near Smithton. The south west and west are mapped as bleached sands with hard-pan or grey-brown pale sands and the Central Plateau is mapped as organic loams with a well-developed O horizon. In 1979, Northcote added to, or, rather, emphasised, the definition of organic soil in that, 'the organic matter amounts should equal or exceed the stated amount, at all depths down to, and including the 30 cm depth' (Northcote 1979). No definition of organic matter is provided and no reference is made to definitions of organic matter. A division of organic horizons is made, however, into O_1 comprising undecomposed organic matter and O_2 comprising organic matter of various stages of decomposition.

The first intensive soil survey in south west Tasmania was for the then Hydro-electric Commission in the late 1970s (Tarvydas 1978). Most of the soils found in this survey were referred to as organic soils and the term was used interchangeably with the term peat. The peats were divided into two sub-types; a reddish-brown fibrous peat and a dark-grey muck peat. No organic content was measured and the definition of organic soil was taken from Northcote (1960) (Tarvydas 1978). Both Northcote (1984) and McDonald and Isbell (1984) refer to organic soil sub-divisions of P1 (fibrous peat) and P2 (muck peat). A series of reconnaissance surveys of Tasmanian land resources during the 1980s by the Soil Conservation Section of the Tasmanian Department of Agriculture provided further insights to the extent and nature of organic soils in Tasmania (Pemberton 1986, 1989; Richley 1984). Richley's work on the north west region differentiated 31 organic soil types on the basis of mineral soil structure, colour and depth (Richley 1984). Examples include: stony black peat, gravelly peat, gravelly black peat, shallow gravelly peat, sandy peat, shallow sandy peat, and silty peat (Richley 1984). No organic contents are provided, although organic soils are stated to cover 15% of the region, almost exclusively on siliceous parent material, with the definition of peat and organic soil following Northcote (1971).

Pemberton (1986) surveyed the Central Plateau region, using the terms peat and organic soils interchangeably, following Nicolls (1958). The terms fibrous and muck are used to describe the upper fibrous root mat and lower, more humified peat. No carbon contents are provided, but from the physical descriptions given of the profiles, the organic soil descriptions include mostly a dominant clay or loam B horizon with a peaty A horizon in all but two profiles described as organic soil. Pemberton (1989) also surveyed the south west region of Tasmania, using the definition of organic soils provided of Northcote (1979, 1984) to describe the soils. Organic matter, in various stages of decomposition, was found to dominate the profile in soils over 30 cm deep. Where soils were less than 30 cm deep, there was little other soil development and shallow peats directly overlaid bedrock or a gravel layer. The organic soil mineral fraction was estimated in the field with a few organic carbon contents provided. Pemberton (1989) introduced several European terms into the organic soil vocabulary of Tasmania in this survey, notably, the terms mire, peatland and blanket bogs. The areas dominated by organic soils, as defined by Pemberton (1989), in the south west, are referred to as peatlands, including acid, mineral-poor 'bogs' and less acid, or alkaline, mineral-rich 'fens'. Organic soils were described in terms of a P_1 fibrous peat horizon and a P_2 muck peat horizon according to Northcote (1984), and in terms on landscape position; organic soils on well-drained slopes and ridges, organic soils in coastal areas, organic soils in lowland depressions, organic soil in alpine and sub-alpine areas, and organic soils associated with forest vegetation. Of around 150 soil profile descriptions, 60 are described as organic soils using only physical soil descriptions and horizon depths. From the physical descriptions, only 41 of those would be considered organosols under the present classification system (Isbell 2002). Seventeen soils, classified as organic (Pemberton 1989), with organic carbon contents for each horizon and horizon depths are provided, with 11 of those confirmed as containing an organic horizon of over 20% organic matter and 8 containing an organic horizon of over 30% organic matter. Under the present classification system (Isbell 2002), only 4 of the 17 soils classified as organic soils (Pemberton 1989) qualify as organosols. Grant *et al.* (1995) also classed mineral soils under scrub and sedgeland-heath, on Precambrian mudstone-sandstone sequences in the north west of Tasmania, as organosols.

Isbell (1992), in developing an Australian organic soil definition, incorporated international organic soil definitions, particularly those of Canada (Agriculture Canada Expert Committee on Soil 1987) and England and Wales (Avery 1980). He included terms describing the degree of humification: fibric, hemic and sapric (Isbell 1992). The present definition (Isbell 2002) differs from that of 1992 in the definition of organic materials, which was made consistent with major international classification systems (Soil Survey Staff 2006, FAO 2006).

1.5 What is known about organic soil forming factors in Tasmania?

1.5.1 Overview

Soil organic matter accumulation is generally accepted as the addition of organic matter in the form of plant and animal detritus through physical, biological and chemical processes (Lal 1993). The major factors affecting the rate of soil organic matter accumulation are climate, biota, parent material, topography and time (Pearsall 1950, Gorham 1953, Moore and Bellamy 1974, Maltby and Crabtree 1976), with an additional factor, fire, needing to be considered in Australia (Northcote *et al.* 1975) and in the United Kingdom (Caseldine and Hatton 1993).

1.5.2 Parent material

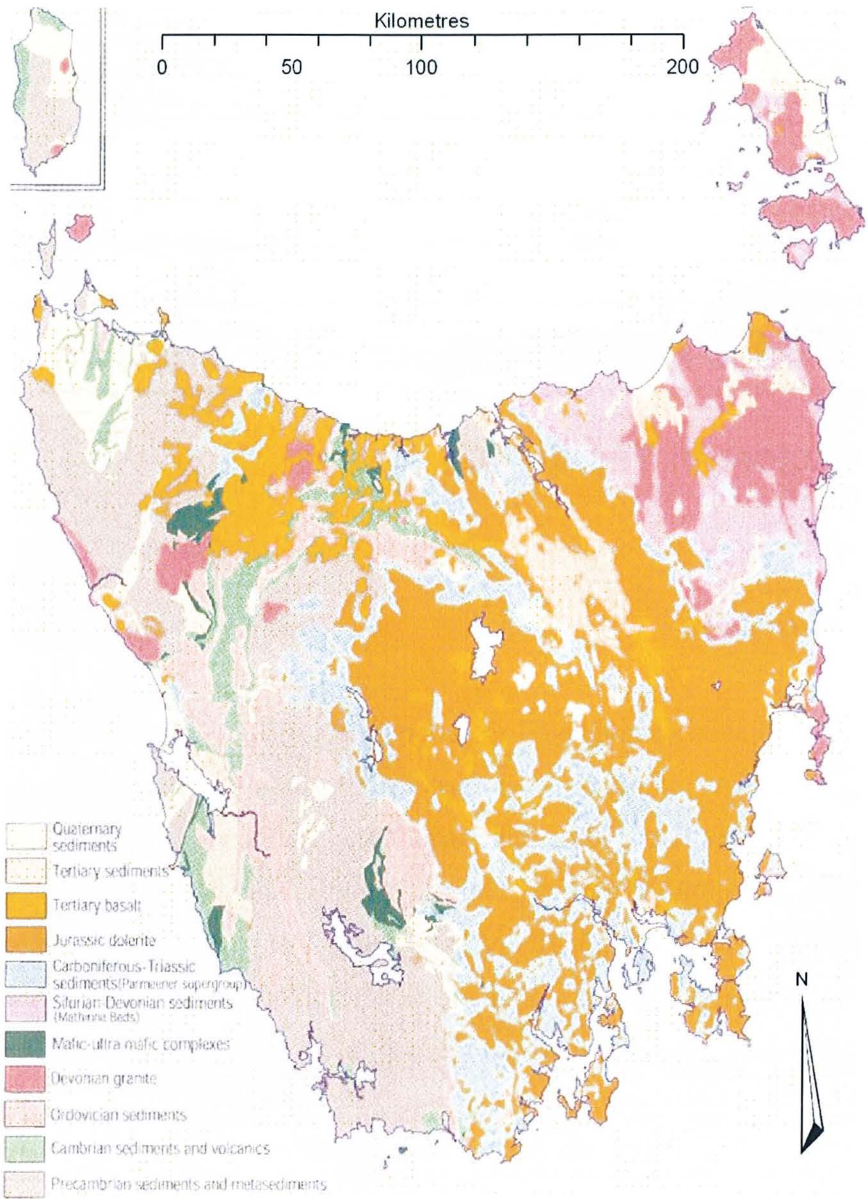

Figure 1.1

Simplified geology of Tasmania taken from Reid *et al.* (1999).

The geology of Tasmania is complex, with Precambrian metamorphosed sediments, Cambrian sediments and volcanics and Quaternary sediments occurring largely in the west of the state and Jurassic dolerite and Carboniferous-Triassic sediments occurring largely in the east of the state (Figure 1.1). Organic soils, or peats, were initially noted as occurring on a wide variety of substrates (Stephens 1953), with no relationship between geology and organic soil inferred. The effect of parent material porosity, weathering characteristics and available nutrients on soil development was noted, particularly by Nicolls and Dimmock (1965) and subsequently by Stace *et al.* (1972). In the absence of soil surveys, Nicolls and Dimmock (1965) used geological maps and surveys to map soils in Tasmania, noting that, within any one climate zone, the pattern of parent material largely determines the distribution of soils, drawing a sharp distinction between the basic igneous rocks basalt and dolerite, and the more siliceous parent materials. Pemberton (1989) suggests that bogs of the south west have formed under the oligotrophic and ombrotrophic conditions provided by the inert quartzite substrate, while a deeper mineral horizon is provided under 'softer' Precambrian substrates of sandstone, phyllite or schist and on Ordovician and Silurian to lower Devonian sediments such as limestone, sandstone or siltstone. A strong role of parent material on soil types in alpine areas in Tasmania has been recognised (Kirkpatrick and Bridle 1998), with deep peats occurring on nutrient-rich substrate on central and eastern mountains, and shallow peats occurring on nutrient-poor substrate on western mountains.

1.5.3 Climate

Climate is an important factor in the development of organic soils, as cold and/or highly moist conditions can favour the accumulation of organic matter (Graf 1981, Solem 1986, Lindsay *et al.* 1988, Wheeler 1992, Halsey *et al.* 1997, McGlone *et al.* 1997a, McGlone *et al.* 1997b, Campbell *et al.* 2000). Stephens (1962) stated that low mean annual temperature is an important environmental factor in the accumulation of organic matter in moor peats as a consequence of low biological and chemical activity, with wet climatic conditions necessary for the formation of acid swamp soils and moor podzol peats. Stace *et al.* (1968) noted that organic soils in Australia are all soils of humid environments. Northcote *et al.* (1975) also mentioned high rainfall as characteristic for organic soil development. Pemberton (1989) mentioned that the factors promoting peat formation in the south west of Tasmania include high rainfall, low evaporation and high relative humidity.

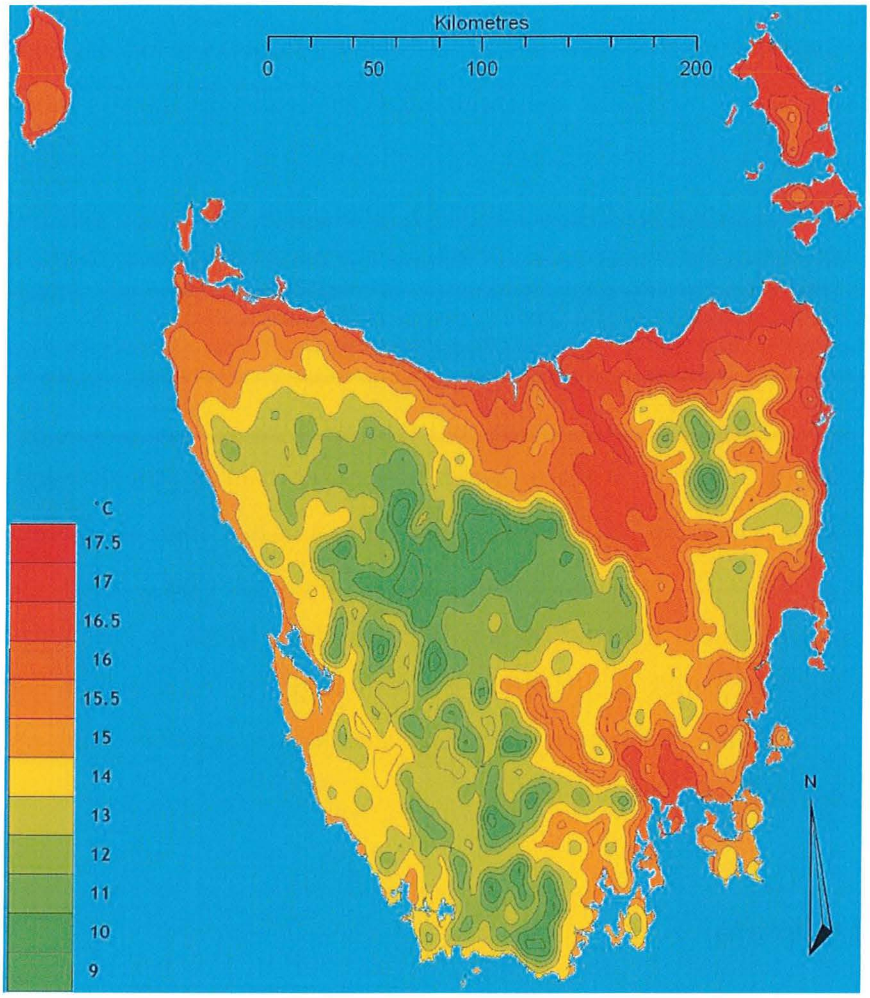

Figure 1.2

Average daily maximum temperature in ° C over the ten years 1996 to 2006 (BOM 2007).

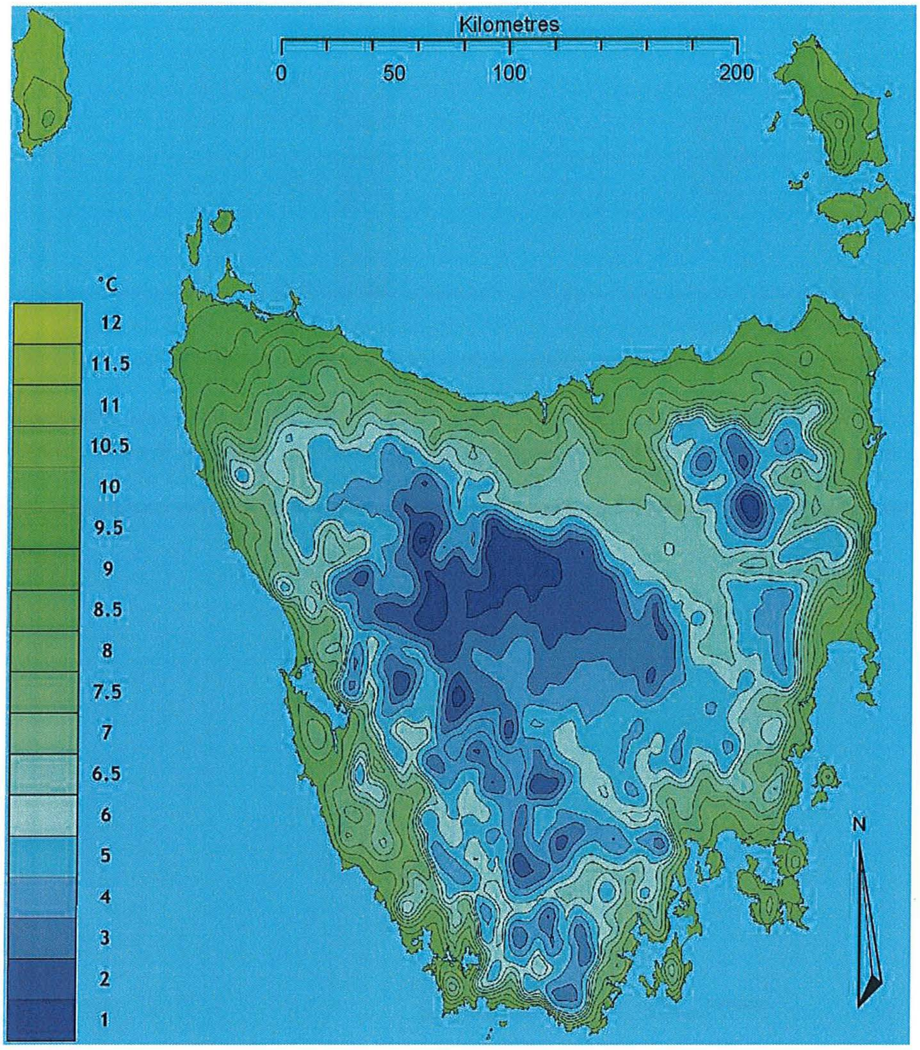

Figure 1.3

Average daily minimum temperature in ° C over the ten years 1996 to 2006 (BOM 2007)

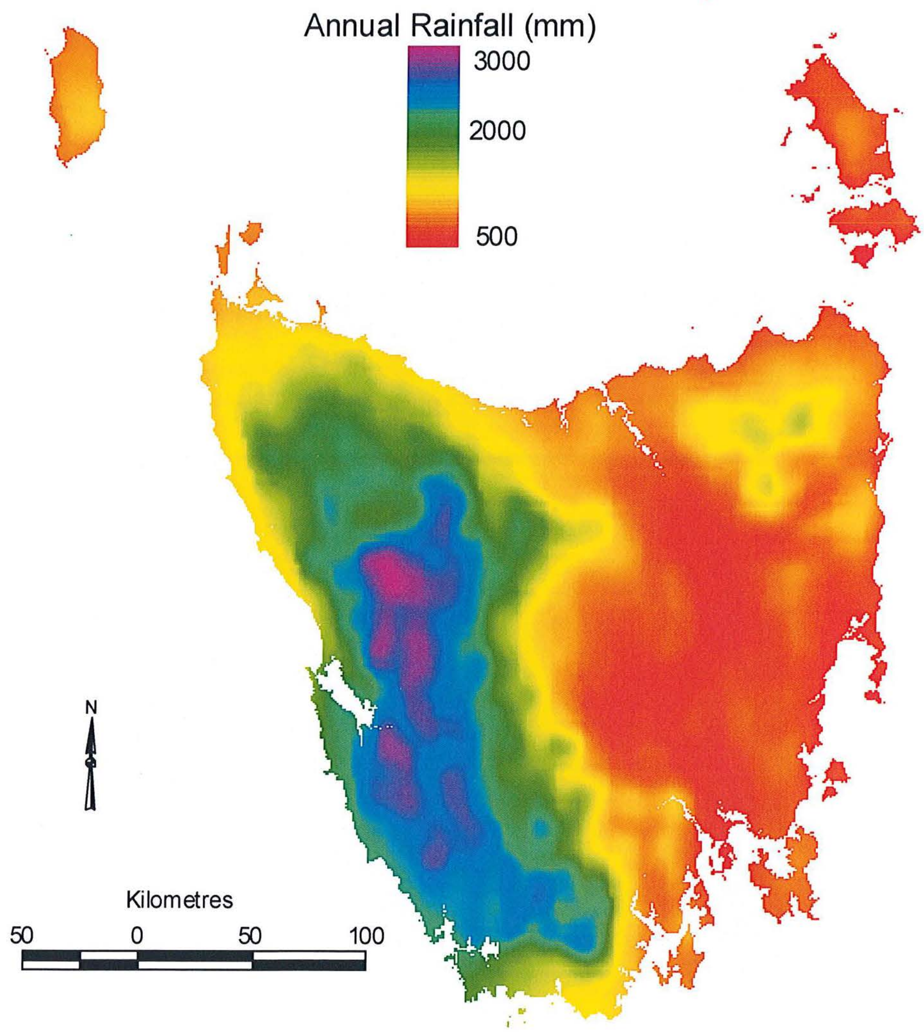

Figure 1.4

Tasmanian average annual rainfall over the ten years 1996 to 2006 (BOM 2007).

Tasmania is located between latitudes 40° and 43°30' south with a temperate maritime climate (Figure 1.2 and 1.3) of mild winters and cool summers (Gentilli 1972). Mountain ranges in the west of the state, and the dominant west and south west wind systems, create a precipitation gradient from west, with > 4, 000 mm of rain p.a., to the east, with < 600 mm p.a. (Figure 1.4). The effect of climate on organic soil accumulation and organic soil character was studied by Bridle and Kirkpatrick (1997) who found that organic soil accumulation (organic matter content and depth) decreased with an increase in altitude on a mountain in the south west of the state. The authors also found that the colour of the organic soil changed from reddish under alpine vegetation to black under buttongrass moorland. A decrease in organic soil accumulation with altitude was attributed to a decrease in plant productivity with decrease in temperature and the slow recovery from fire in alpine plant communities. Whinam (1990) concluded that Tasmanian regions where *Sphagnum* and *Sphagnum* mires are found are generally drier than in the northern hemisphere mire regions due to warmer temperatures experienced in Tasmania resulting in less effective precipitation. Other researchers (Jarman *et al.* 1988b, Bridle 1994) have recognised that temperatures in Tasmania are warmer than those considered optimal for peat growth, using the criteria of Lindsay *et al.* (1988), although total annual rainfall and total annual rain days are more than adequate to produce the humid conditions necessary for organic soil accumulation (Lindsay *et al.* 1988). It has been suggested that the shallow Tasmanian organic soils have reached an organic accumulation equilibrium (Balmer 1991) where decomposition balances litter input (Chadwick *et al.* 1994).

1.5.4 Topography

Topography has been reported as important for organic soil accumulation through its effects on hydrological regimes (Moore and Bellamy 1974, Ivanov 1981, Charman 1993, Lindsay 1995, Graniero and Price 1999, Edom 2001, Succow 2001). Topographic effects, especially slope shape and landscape position, on soil organic accumulation have also been studied for mineral soils (Schimel *et al.* 1985, Pennock 1997, Gregorich *et al.* 1998). Soil organic matter increases downslope, with the least amount of soil organic matter on convex slopes or shoulder elements of slopes and the highest accumulation of organic matter at the toe of a slope (Pennock 1997). Of particular interest is that soil organic matter has been found to be difficult to re-establish on convex slopes due to a loss of soil organic matter leading to restricted plant growth and therefore litter input (Gregorich *et al.* 1998).

In Australia, organic soil accumulation has been related to topography from the outset of soil classification. For example, Stephens (1962) describes skeletal soils as occurring on rugged topography which ensures that natural erosional processes remove soil as fast as it is formed. Nicolls and Dimmock (1965) also attribute most Tasmanian peat development to poor drainage on valley floors and flood plains, with deeper peats occurring on wetter sites. Stace *et al.* (1968) conclude that all organic soil types, with the exception of alpine humus soils, are found in topographic situations in which ground water accumulates. Northcote *et al.* (1975) states that organic soils occur in low-lying, poorly drained areas in areas of high rainfall and on hillslopes and elevated sites in cold regions where rainfall is high and constant. Tarvydas (1978) classified the soil profiles in his survey on the basis of slope and also noted a difference in peat type with topography, with well-drained profiles associated with slopes or in some elevated, flat positions, developing a reddish-brown, soft fibrous peat and, a dark grey muck peat developing on flat, waterlogged areas. Both Brown and Podger (1982) and Bowman *et al.* (1986) found that structureless muck peats occur on poorly-drained sites with fibrous organic soils developing with better aeration. Pemberton (1989) notes that the deepest peats occur in localised, poorly-drained depressions in the south west of the state, with shallower peats on slopes which are characteristically more fibrous. Pemberton (1989) and Tarvydas (1978) found that organic soil depth was topographically related with shallow soils of typically less than 30 cm on slopes, with little or no organic soil on slopes of over 40° (Pemberton 1989). Whinam (1990) also notes the effect of topography on drainage on the occurrence of *Sphagnum* peats, with the deepest *Sphagnum* peats occurring in localised deep depressions, for example kettle holes, and shallow, 'pillow' deposits occurring on slopes on seepage lines.

1.5.5 Biota

Organic accumulation has been shown to derive from the above and below ground biomass (Clymo 1983, Succow 2001). The amount, placement and chemical composition of organic residues of vegetation also effect organic matter accumulation (Quideau *et al.* 2000). Previous studies in Tasmania have touched lightly on the effect of vegetation on organic soil accumulation with Stace *et al.* (1968) attributing the accumulation of humified organic matter in alpine humus soils to herbaceous vegetation remains and weak weathering of the mineral fraction. Stace *et al.* (1968) also attribute the development and character of neutral to alkaline peats to the type of vegetation forming the plant debris, with tea-tree forests giving rise to black granular peats and sedge meadows giving rise to more fibrous peat. In Tasmania, Stephens (1962) noted that moor peats and alpine humus soils owed their genesis partly to the slow, but positive, accumulation of organic matter from the associated alpine flora. Stephens (1968) acknowledged the role of *Gymnoschoenus sphaerocephalus* moor podzol peats in Tasmania. Stephens (1968) also partly attributed accumulation of organic matter in acid swamp soils to the associated vegetation. Tarvydas (1978) observed that the organic soils were the lifeline of the vegetation ecosystem in the surveyed valleys in the south west of Tasmania where the tallest and densest forests occur on areas of fibrous peat, with no forest vegetation on muck peats. The difference in forest and moorland peat was also note by Pemberton (1989) where, on examining sedgeland/heath - forest boundaries, he found that the forest had a shallow surface layer of reddish, fibrous peat while the sedgeland/heath had deeper, fibrous, followed by muck peat. However, the emphasis from the previous three authors was on vegetation occurring on specific organic soil types, rather than vegetation influencing organic soil characteristics.

Jarman *et al.* (1982) found that in the Lower Gordon area of south west Tasmania, forest and older scrub communities developed red brown fibrous peats; well-drained sedgeland-heath developed dark fibrous peats or root mats and poorly-drained sedgeland-heaths developed muck peats. Jarman *et al.* (1982) further suggested that organic soils beneath any given community were conditioned by vegetation type. Brown and Podger (1982) found that peat depth was controlled by both the growth rates and litter accumulation of the plants present at Bathurst Harbour in the south west of Tasmania and that the type of peat found appeared to be a function of both the vegetation type and local drainage, but that local drainage, in itself, was conditioned by the vegetation to some extent. For example, *Gymnoschoenus sphaerocephalus* produced local ponding and silting on otherwise well-drained slopes. Bowman *et al.* (1986) found that anaerobic conditions in sedgeland-heath are primarily related to poor hydrological conductivity in the upper soil horizons rather than being related to a perched water table following hard pan formation through podsolisation. They also suggested that anaerobic conditions are further encouraged by the low transpiration rates of the particular vegetation and that soils under forest on Tasmanian quartzite in the south west of the State, have accumulated nutrients over time on well-developed peats.

In swamp forest in north west Tasmania, Pannell (1992) noticed that peat largely comprises the roots of *Nothofagus cunninghamii*, *Phyllocladus aspleniifolius* and *Melaleuca ericifolia,* with *Nothofagus cunninghamii* occurring only on sites with a fibrous peat horizon. Pannell (1992) suggested that this species produces its own fibrous peat mounds from its leaf, bark and root litter and also reports *Melaleuca ericifolia* developing substantial amounts of fibrous peat around its stems and roots. Numerous studies on *Sphagnum* in Tasmania (Whinam *et al.* 1989, Whinam 1990, Whinam and Buxton 1997, Whinam and Chilcott 2000, Whinam *et al.* 2003) have shown that the occurrence of *Sphagnum*, restricted to fertile geology and wet conditions, will nevertheless create a highly organic soil type in Tasmania, formed from the plant remains of *Sphagnum* species and associated vegetation.

The effects on organic soil of the fauna living within the soil matrix have been discussed for the freshwater burrowing crayfish species found throughout organic soils in Tasmania (Richardson and Swain 1978, Richardson 1983). These species create burrow systems in the organic soils, with the effect of aerating the soils, increasing drainage (Richardson 1983) and mixing the profile (Richardson and Swain 1980), so that the lower mineral horizons are often found to be mixed with the upper organic horizons.

1.5.6 Time

The amount of time that the soil has had to develop has been considered by Pemberton (1998) and Macphail *et al.* (1999) in relation to the past glacial retreat, post glacial climate and disturbance history. Radio-carbon dating of terrestrial organic soils is problematic in Tasmania through possible contamination of carbon from younger humic acids in groundwater (Colhoun 1986), although cores and correlated palynological data have indicated basal organic soil formation at the start of the Holocene for Melaleuca at sea level in the south west (Macphail *et al.* 1999) with a similar age at a low-lying coastal site near Strahan in the west (Fletcher unpub. data). Basal dates of organic soil accumulation have been given at 11,820 ± 100 BP in the Middle King Valley in western Tasmania at 210 m a.s.l. (Colhoun *et al.* 1992) and 13,010 ± 130 BP at Governer Bog in the King Valley, western Tasmania at 180 m a.s.l. (Colhoun *et al.* 1991). Younger dates have been produced for terrestrial inland south western Tasmania at 930 ± 40 BP (Tye 2002) at around 350 m a.s.l. and Central Plateau areas: 8,270 ± 270 BP at the Walls of Jerusalem at 1,000 m a.s.l. and 8, 575 ± 125 BP at the southern end of the Central Plateau at 1,200 m a.s.l. (Macphail 1979). Possible contamination of the terrestrial core through contact with washed in, younger humic acids, destruction of all or part of the soil profile through disturbance, fire or erosion and uneven accumulation and oxidation serve to confuse the chronosequence. An example of this is the recording of *Pinus* spp. pollen, an exotic taxon associated with the arrival of Europeans, found at the base of a terrestrial organic soil, which was dated at 5,200 BP (Macphail *et al.* 1999). The amount of Poaceae pollen found in the same zone, led the researchers to date the position between 19,000 BP and 12,000 BP, based on correlations with similar Poaceae counts in the region (Macphail 1979, Macphail *et al.* 1999).

1.5.7 Fire

Disturbance through burning has been reported as an important factor affecting organic matter accumulation, particularly in Australian soils (Northcote *et al.* 1975) with burning reported to have detrimental effects on organic soil matter accumulation through the incineration of the litter (Northcote *et al.* 1975) and more humified organic material (Bowman and Jackson 1981, Wein 1981, Bridle *et al.* 2003). Northern hemisphere studies have shown that burning can destroy peat profiles through oxidation and subsequent erosion (Bower 1959, Tallis 1973, 1985, 1987, Racine 1979, Radcliffe and Osvald 1988, Maltby *et al.* 1990). Burning can maintain peat development in areas of low-lying relief due to the removal of trees, shrubs or vegetation, which in turn reduces interception and transpiration, resulting in increased catchment water levels and raised water table levels which encourage paludification (Caseldine and Hatton 1993, Moore 1993, Speranza *et al.* 2000).

Charcoal in the soil has also been shown to reduce soil porosity leading, again, to higher, or even perched, water tables (Mallik *et al.* 1984, Moore 1993). Burning of vegetation on organic soils in the northern hemisphere has also been noted to cause nutrient losses (Allen 1964). Nitrogen and phosphorus are depleted in instances where the organic surface mat has been burned (Allen 1964). Bare, darker soil surfaces following burning are more readily heated than vegetated surfaces (Thompson 1987), leading to an increased biological activity and organic matter decomposition (Morrissey *et al.* 2000).

In Scotland, there is a practice of burning *Calluna vulgaris* associated moorland vegetation (muirburn) on a 10-15 year cycle in order to maintain a mosaic of habitats to increase numbers of the game bird *Lagopus lagopus scoticus*. The damaging effects of escaped *Calluna vulgaris* muirburn on deeper peats has been well documented (Rowell 1988, Brooks 1997) and careful management of these moorlands has been suggested in order to ensure cool burns (Rowell 1988), which maintain wetter moorland surface conditions in certain topographic positions (Chapman and Rose 1991). Managed burns are also carried out on Tasmanian buttongrass moorland containing the highly pyrogenic *Gymnoschoenus sphaerocephalus*, to reduce fuel loads and therefore minimise fire-risk in more sensitive vegetation types (Marsden-Smedley *et al.* 1999). Few studies have considered the direct effects of wildfire or managed burns on Tasmanian organic soils, although the shallow nature of the Tasmanian organic soils, and the skeletal soils of the west and south west of Tasmania have been attributed to fire and subsequent erosion removing a previous peat surface (Macphail *et al.* 1999) with an estimated 100,000 ha of blanket bog proposed to have been degraded in this way (Pemberton 1988, 1989, Pemberton and Cullen 1995). Peat loss has also been noted in Tasmanian alpine areas following fire (Kirkpatrick and Dickinson 1984a) and in organic soils in the north west of Tasmania (Wein 1981). No studies have quantified removal or change in soil organic carbon through either wildfire or managed burns on organic soils in Tasmania.

Interactions between vegetation, soil nutrients and burning have been studied in Tasmania more thoroughly with burn frequency reported as an important factor in vegetation composition, vegetation structure and soil cover in Tasmania (Jackson 1968, Brown and Podger 1982, Ogden 1985, Kirkpatrick and Bridle 1998, Brown *et* *al.* 2002). Vegetation throughout Tasmania has been very much affected by fire. Fire has been attributed to both lightning strikes and Aboriginal burning practices over the last 40,000 years (King 2004, King *et al.* 2006). A change in fire management with the removal of Aborigines and less frequent, but more destructive, fires occurring as a result of an accumulated fuel load has been suggested by Marsden-Smedley (1998).

Vegetation types display differences in vegetation recovery and sensitivity to fire disturbance. Alpine and montane vegetation and montane and high altitude rainforest show an extremely slow recovery from fire, with no recovery from fire evident in certain communities (Jackson 1973, Kirkpatrick and Dickinson 1984a, Kirkpatrick 1986).

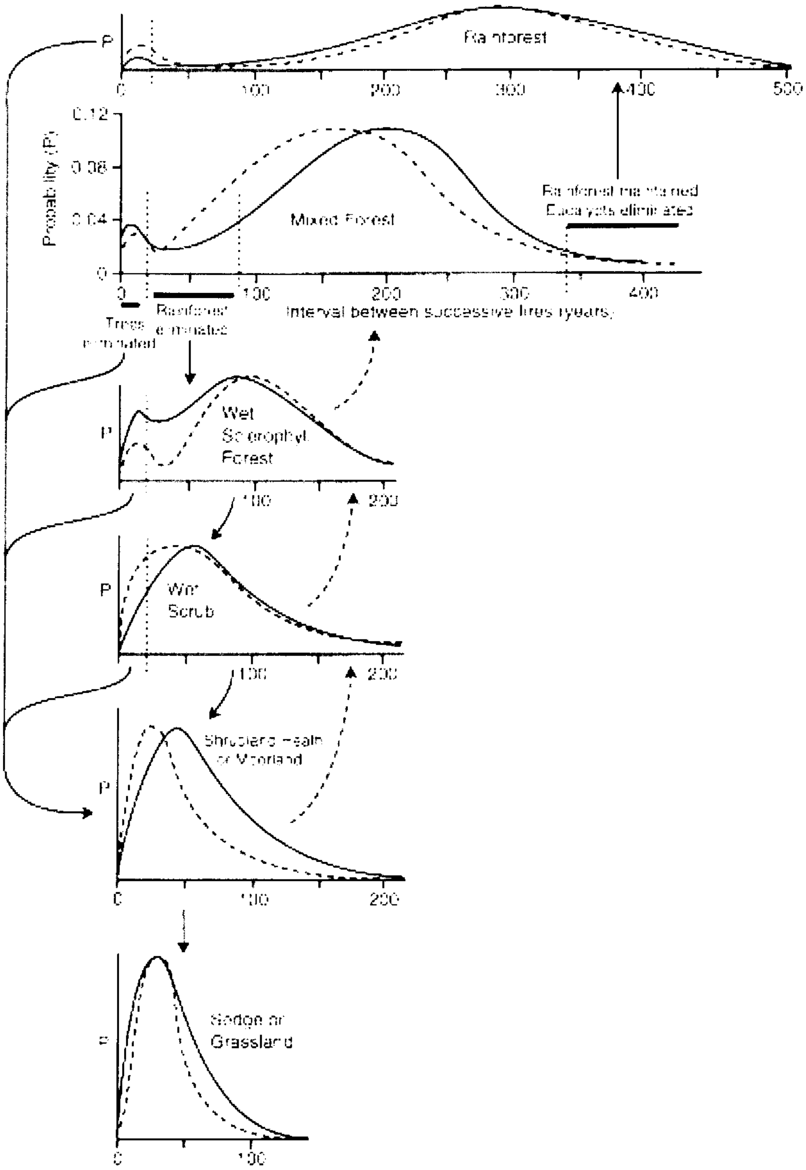

Figure 1.5

Ecological fire succession model adapted from Jackson (1968) and Bowman and Jackson (1981). The flow diagram shows the assumed probability distributions for fire-free intervals in mixed forest, rainforest, wet sclerophyll forest, wet scrub, sedgeland and sedgeland-heath in western Tasmania. Shifts from one vegetation type to another are assumed to be governed by specified fire- free intervals. Solid arrows show transitions arising from two fires occurring in quick succession, killing regenerating woody plants before they can reach sexual maturity. Dashed arrows show transitions arising from the interval between two successive fires being long enough to allow the establishment and sexual maturity of the long-lived plants that would otherwise be eliminated by shorter fire-free intervals. Solid graph lines are from Jackson's (1968) model and dashed graph lines are from Bowman and Jackson's (1981) re-interpretation. Taken from Hill (2000).

In lowland vegetation where organic soils are found, predominantly in the west and south west of the State, the pattern of vegetation in the form of sedgeland-heath, scrub, wet eucalypt forest and rainforest has been attributed to the effects of fire and site fertility (Jackson 1968). The 'ecological drift' model proposed by Jackson (1968) (Figure 1.5), proposes that long intervals between burning will lead to rainforest vegetation which, in turn, lowers the risk of fire occurring at that site in the future. Shorter intervals between fire events will lead to sedgeland-heath vegetation which is highly pyrogenic and can burn within 24 hours of rainfall (Marsden-Smedley and Catchpole 1995). Therefore, the risk of fire is greater than in surrounding vegetation. The ecological drift model has been supported for lowland vegetation types: sedgeland-heath, scrub, wet eucalypt forest, mixed forest and lowland rainforest (Kirkpatrick 1977a, 1977b, Bowman and Jackson 1981, Brown and Podger 1982, Jarman *et al.* 1982, Podger *et al.* 1989).

Brown and Podger (1982) concluded that there was also a strong association between soil type and vegetation type and that the intensity of fires, as well as the frequency, was important in changing edaphic conditions, especially in aerated peat. They suggested that very intense fires, removing surface peat, would result in a more permanent vegetation change than a light fire which left vegetation thatch and surface peat intact, which would result in no long-term vegetation change. Brown and Podger (1982) stated that, on aerated sites, after fire, if no further fires occur, the vegetation changes from sedgeland-heath, through scrub to sclerophyll forests (with or without eucalypts present) and eventually to rainforest after 100 to 500 years. On nutrient-poor sites the timescales are extended compared to nutrient-rich sites. It has been suggested that, on the most nutrient-poor sites, the succession may be halted in a semi-permanent disclimax (Macphail 1980) or an edaphic climax (Fletcher pers. comm.).

A topographic effect on fire frequency has been noted (Jarman *et al.* 1982). Drier sites, such as ridge tops, will dry out before wetter sites, such as gullies, with the drier sites therefore more susceptible to fire disturbance. The effects of fire on soil nutrients has been studied, with the conclusion that fire reduces the organic content and decreases fertility by interrupting succession to species with more nutrient-rich foliage (Bowman and Jackson 1981, Bowman *et al.* 1986). Bowman *et al.* (1986) further suggest that where fire is intense, the nutrient-rich organic layer can be destroyed and a slow recovery results, as the accumulation of nutrients in the soil necessary for succession, must come from cyclic salt input not the oligotrophic environment. It therefore seems that the relationship between the succession of vegetation following disturbance and edaphic conditions are highly related and that fire, in terms of its frequency and intensity, is an important environmental factor in characterising organic soil, both in terms of the effect of fire directly on the organic soil and indirectly on the overlying vegetation, which in turn effects the nature of the soil.

1.6 Knowledge gap

At present, the soil order, organosols, has been used to describe the organic soils throughout Australia, including Tasmania, using terminology taken from Northern Hemisphere regions (Avery 1980, Nyborg and Solbakken 2003, Soil Survey Staff 1998) with very different organic soil forming vegetation and climate. The typical Northern Hemisphere organosol-producing taxon is *Sphagnum*, which is responsible for a very small area of organosol in Tasmania, the rest forming mostly under Restionaceae and Cyperaceae species in the treeless moorlands and also under alpine vegetation, scrub and rainforest vegetation. No extensive, exclusively organic soil surveys have been carried out for the purpose of classifying organic soil and very little is therefore known about the organic soils of Tasmania. Small-scale studies, isolated soil pits and research that has focussed predominantly on vegetation has often referred to soils under buttongrass moorland and certain alpine and sub-alpine communities as peats, and peatland (Stace *et al.* 1972, Nicolls 1957, Tarvydas 1978, Brown and Podger 1982, Bowman *et al.* 1986, Whinam *et al.* 2001), but the examples provided do not always contain the required percent of organic carbon and do not always meet the depth requirements for both the national definition of an organosol or the international definitions of peat and peatland reviewed in chapter 2.

1.7 Aims of the thesis

The confusion in terminology requires remediation and a more precise survey of organic soils and their extent is therefore required. A description of the characteristics of the organic soils, the environments under which they are found and their areal extent is essential to ensure a common terminology is understood and used. The aim is therefore to produce a classification of the organic soils, based on measurable soil properties and to then relate the characteristic organic soil properties to environmental factors. The relationship between organic soil characteristics and environmental factors will enable predictive mapping of the occurrence and organic content of organic soils in Tasmania.

1.8 Structure of thesis

Chapter 2 addresses the question: what are the present national and international organic soil and organic soil landform classifications?

Chapter 3 addresses the question: what intrinsic soil properties best characterise Tasmanian organic soils?

Chapter 4 addresses the question: what environmental factors are significantly correlated with the organic soil cluster groups?

Chapter 5 addresses the question: which environmental factors can be used to classify and predict organic soil characteristics?

Chapter 6 addresses the questions: what are the relationships between the dominant environmental factors and organic soil? Can the dominant environmental factors, available as GIS layers, be used to predict: the location and extent of organic soils, and carbon stocks?

Chapter 7 addresses the questions: what is the relationship between the organic soil classifications currently in use for Tasmania and the proposed revision? How does the organic soil classification compare with current landform classifications?

Chapter 8 addresses the question: what are the management implications of the main findings of the thesis?

Chapter 2

Soil and Landform Classifications

2.1 Introduction

2.1.1 Correlations between soil classification systems

Numerous systems of soil taxonomy have been developed, mostly relevant to agriculture and engineering (Brasfield 1984). Knowledge of soils is geographically patchy, with developed regions and regions suitable for agricultural development better known than others. There is therefore an uneven base for an international system of classification. All of the soil taxonomies and classifications outlined are hierarchical with the taxa defined on the basis of measurable or observable soil properties. However, they differ in several aspects. The New Zealand, Australian, English and Welsh and Canadian systems are designed for only those soils occurring in the country of classification, whereas Soil Taxonomy (Soil Survey Staff 2006) and World Reference Base for Soil Resources (WRB) (FAO 2006) are international in scope. The consideration of horizons as diagnostic in Soil Taxonomy and the English and Welsh Classification is limited to biological activity, rooting depth or plough depth at 2 m and 1.5 m respectively, where other soil classifications have no depth limit. Not all systems follow the method of soil classification through identification of a control section and some systems provide more details than others on the thicknesses and depths of a control section. Criteria related to the depths and organic carbon content of organic materials are also not comparable across the various systems. There has been a tendency to develop common definitions. However, common definitions have not yet been completely achieved. In the national taxonomies and Soil Taxonomy, the criteria for differentiating taxa at the various categorical levels are not precise. In these hierarchical systems of soil classification, logical groupings of soils that reflect soil-forming factors have been found to be unobtainable by using systematic frameworks, in which all taxa at the same categorical level are differentiated based on uniform specific criteria (Young and Hammer 2000). Soil properties are used as criteria in these hierarchical classifications, rather than environmental factors or use criteria (Joel 1926, Webster 1968). The ways that the major soil taxonomies (World Reference Base for Soil Resources (FAO 2006), Soil Taxonomy (Soil Survey Staff 2006), The Canadian Soil Taxonomy (Soil Classification Working Group 1998), The New Zealand Soil Classification (Hewitt 1998), The English and Welsh Soil Classification (Avery 1980) and the Australian Soil Classification (Isbell 2002) treat organic soils are described and discussed below.

2.2 Soil Taxonomies

2.2.1 World Reference Base for Soil Resources (WRB) (FAO 2006)

The latest version of the WRB (FAO 2006) was agreed upon at the World Congress of Soil Science with the intention of developing and improving international communication regarding soil. Certain regions and countries have adopted the WRB nomenclature and classification as their official system, and others have adopted the WRB as the higher level of their national soil classification system.

The WRB is a two level, hierarchical, morphological-genetic system, currently consisting of two tiers, the first of which identifies the 32 Reference Soil Groups (RSGs). The second tier gives a further level of detail by adding a set of uniquely defined qualifiers to the RSGs. A logical key is used to identify soils and attribute a RSG, allocated on the basis of soil-forming factors or processes which most clearly influence the soil formation. Soil is considered to a depth of 2 m from the surface with the primary division being that between organic and mineral soil, with organic soil called histosols (FAO 2006). The WRB definition of a histosol is as follows (FAO 2006):

> Soils having organic material, either
>
> 1. 10 cm or more thick starting at the soil surface and immediately overlying ice,

continuous rock, or fragmental materials, the interstices of which are filled with organic material; or

2. cumulatively within 100 cm of the soil surface either 60 cm or more thick if 75 percent (by volume) or more of the material consists of moss fibres or 40 cm or more thick in other materials and starting within 40 cm of the soil surface.

The WRB qualifier levels are set for each RSG with the qualifiers for histosols provided in Table 2.1. Qualifiers that are typically associated with the particular RSG and intergrades are given as prefixes and other qualifiers given as suffixes, such as those related to diagnostic horizons, properties or materials, or physical, surface, mineralogical and textural characteristic or colour. Specifiers can be used to indicate depth of occurrence, or to express intensity of soil characteristics.

Table 2.1

The list of WRB prefix and suffix qualifiers and specifiers for the RSG histosol (FAO 2006).

Prefix qualifiers	*Suffix qualifiers*	*Specifiers*
Folic	Thionic	Bathy
Limnic	Ornithic	Cumuli Endo
Lignic	Calcaric	Epi
Fibric	Sodic	Hyper
Hemic	Alcalic	Hypo
Sapric	Toxic	Ortho
Subaquatic	Dystric	Para
Glacic	Eutric	Proto
Rheic	Turbic	Thapto
Technic	Gelic	
Cryic	Ombric	
Leptic	Petrogleyic	
Vitric	Placic	
Andic	Drainic	
Salic	Transportic	
Calcic	Novic	

The minimum depth for histosols is 10 cm which may exclude organic soils on slopes, especially short, convex slopes in Tasmania. Another possible RSG to consider for Tasmanian organic soils would be leptosols which are defined as soils having one of the following (FAO 2006):

a. limitation of depth by continuous rock within 25 cm of the soil surface, or
b. less than 20 percent (by volume) fine earth averaged over a depth of 75 cm from the surface or to continuous rock, whichever is shallower; and

no calcic, gypsic or spodic horizon.

The WRB qualifier levels and specifiers for leptosols are provided in Table 2.2.

Table 2.2

The list of WRB prefix and suffix qualifiers and specifiers for the RSG leptosol (FAO 2006). Definitions and example are provided in Appendix 2.

Prefix qualifiers	*Suffix qualifiers*	*Specifiers*
Haplic	Brunic	Bathy
Nudilithic	Gypsic	Cumuli
Lithic	Calcaric	Endo
Hyperskeletic	Ornithic	Epi
Rendzic	Tephric	Hyper Hypo
Folic	Humic	Ortho
Histic	Sodic	Para
Technic	Dystric	Proto
Vertic	Eutric	Thapto
Salic	Oxyaquic	
Gleyic	Gelic	
Vitric	Placic	
Andic	Greyic	
Stagnic	Yermic	
Mollic	Aridic	
Umbric	Skeletic	
Cambic	Drainic	
Haplic	Novic	

The WRB does not include climatic descriptors, nor does it contain the detail possible at a national level for organic soils, such as dominant organic-forming material or differentiating underlying geology. The WRB was produced as a comprehensive classification system, enabling accommodation with national classification systems, but with its main focus being on the international communication and compilation of soil databases. A third tier is therefore suggested at national level (FAO 2006).

2.2.2 Soil Taxonomy (Soil Survey Staff 2006)

The most comprehensive and widely used soil classification system in use in the United States is the Soil Taxonomy produced by the United States Department of Agriculture and Natural Resources Conservation Service (Soil Survey Staff 2006). Soil Taxonomy is a hierarchical classification system that is under constant revision, incorporating results of soil research. Soils are differentiated through the use of a key which uses diagnostic horizons and diagnostic soil characteristics to assign soils. Both the diagnostic horizons and soil characteristics reflect research on pedogenic processes and are defined by measurable morphological and chemical properties. Many of the features of the Soil Taxonomy have been used in the WRB, which is particularly apparent in the divisions of organic soils based on decomposition and depths of soil, and also in the 2 m depth and the primary division of soils in the key into organic and mineral soils. This primary division describes non-gelic organic soils as follows (Soil Survey Staff 2006):

> Organic soils have organic soil materials that:
>
> 1. Do not have andic soil properties in 60 percent or more of the thickness between the soil surface and either a depth of 60 cm or a densic, lithic, or paralithic contact or duripan if shallower; and
> 2. Meet one or more of the following:
>   a. Overlie cindery, fragmental, or pumiceous materials and/or fill their interstices and directly below these materials have a densic, lithic, or paralithic contact; or
>   b. When added with the underlying cindery, fragmental, or pumiceous materials, total 40 cm or more between the soil surface and a depth of 50 cm; or
>   c. Constitute two-thirds or more of the total thickness of the soil to a densic, lithic, or paralithic contact and have no mineral horizons or have mineral horizons with a total

thickness of 10 cm or less; or

d. Are saturated with water for 30 days or more per year in normal years (or are artificially drained), have an upper boundary within 40 cm of the soil surface, and have a total thickness of either:

    1. 60 cm or more if three-fourths or more of their volume consists of moss fibers or if their bulk density, moist, is less than 0.1 g/cm^3; or
    2. 40 cm or more if they consist either of sapric or hemic materials, or of fibric materials with less than three-fourths (by volume) moss fibers and a bulk density, moist, of 0.1 g/cm^3 or more; or

e. Are 80 percent or more, by volume, from the soil surface to a depth of 50 cm or to a glacic layer or a densic, lithic, or paralithic contact, whichever is shallowest.

It is a general rule that a soil is classified as an organic soil (histosol) if more than half of the upper 80 cm of the soil is organic or if organic soil material of any thickness rests on rock or on fragmental material having interstices filled with organic materials.

Diagnostics are then provided for organic soils, with an initial division into the suborders: fibric, hemic, sapric and folic organic soils, representing degree of decomposition of organic materials and water table regime. Histosol suborders are further divided into great groups based on the presence of *Sphagnum* species, humilluvic materials, a sulfuric horizon, climatic classes and temperature regime. Subgroups are based on the dominance of a particular organic material in the profile, the fibre content of the organic materials, the thickness of the organic layers or type of underlying mineral material if the organic layers are shallow. Families are based on more specific site conditions such as acidity, soil depth, and soil temperature and the final division is into series which differentiate individual soil units at a local scale. Depth is used to define control sections for use in definitions within the order histosols. Consideration of depth is also used to distinguish low bulk density organic accumulating plants such as *Sphagnum* in the surface tier. The differentiae used for histosols are shown in Table 2.3 and result in 60 recognised subgroups.

Table 2.3

Differentiae used in the Soil Taxonomy order histosols (Soil Survey Staff 2006) yielding a total of 60 subgroups. Family differentiae may be used with any of the sub groups.

sub order	*great group*	*sub group*	*family*
Fibrist	Cryofibrist	Hydric-, Terric-, Lithic-, Fluvaquentic-, Shagnic-, Typic-	Particle size classes • Fragmental • Sandy • Sandy-skeletal • Loamy-skeletal • Clayey-skeletal • Clayey • Loamy Mineralogy classes • Ferrihumic • Coprogenous • Diatomaceous • Marly Reaction classes • Euic • Dysic Soil Temperature Classes • Hypergelic • Pegelic • Subgelic • Frigid • Mesic • Thermic • Hyperthermic • Isofrigid • Isomesic • Isothermic • Isohyperthermic
	Haplofibrist	Hydric-, Lithic-, Limnic-, Terric-, Fluvaquentic-, Hemic-, Typic-	
	Sphagnofibrist	Hydric-, Lithic-, Limnic-, Terric-, Fluvaquentic-, Hemic-, Typic-	
Folist	Cryofolist	Lithic-, Typic-	
	Torrifolist	Lithic-, Typic-	
	Ustifolist	Lithic-, Typic-	
	Udifolst	Lithic-, Typic-	
Hemist	Sulfohemist	Typic-	
	Sulfihemist	Terric-	
	Luvihemist	Typic-	
	Cryohemist	Hydric-, Lithic-, Terric-, Fluvaquentic-, Typic-	
	Haplohemist	Hydric-, Lithic-, Limnic-, Terric-, Fluvaquentic-, Fibric-, Sapric-, Typic-	

sub order	*great group*	*sub group*	*family*
Saprist	Sulfosaprist	Typic-	
	Sulfisaprist	Terric-, Typic-	
	Cryosaprist	Lithic-, Limnic-, Terric-, Fluvaquentic-, Typic-	
	Haplosaprist	Halic-, Lithic-, Limnic-, Terric-, Fluvaquentic-, Hemic-, Typic- HalicTerric-	

Families are further divisible into series based on any property used as criteria at higher levels in the system with commonly used criteria comprising: horizon properties, depth and thickness, texture, mineralogy, soil moisture, soil temperature and amounts of organic matter.

Although the classification is complicated by different horizon thickness and organic soil depth requirements at each level, there is representation of the large range of climatic conditions found in the United States under which organic matter accumulation occurs. Different soil water regimes and vegetation giving rise to organic accumulation are also represented within the upper levels of the taxonomy, with acidity differentiators possible at the family level.

2.2.3 Canadian Soil Taxonomy (Soil Classification Working Group 1998)

The Canadian system of soil taxonomy is restricted to soils found within Canada, although it is closely related to the US Soil Taxonomy. The Canadian Soil Taxonomy is hierarchical with conceptual classes that are based on soil properties (Soil Classification Working Group 1998). Taxa are defined on the basis of observable and measurable soil properties that reflect processes of soil genesis and environmental factors. This is highlighted by the diagnostic criteria for the higher level taxa which reflect the outcomes of processes of soil genesis. The system follows both the WRB and Soil Taxonomy systems by using a key with classes defined on the basis of specific properties, but the resulting taxa reflect, to as great an extent as possible, genetic or environmental factors. The hierarchical levels are: order, based on properties of the pedon that reflect the nature of the soil environment and the effects of the dominant soil-forming processes; great group, based on properties that reflect differences in the strengths of dominant processes, or a major contribution of a process in addition to the dominant one; subgroup, based on the kind and arrangement of horizons that indicate conformity to the central concept of the great group, intergradation with soils of another order, or additional special features within the control section; family, based on parent material characteristics, such as particle size, mineralogy, calcareousness, reaction, and depth, and on soil climatic factors; series, based on detailed features of the pedon. Pedons belonging to a series have colours, textures, structures, consistencies, thicknesses, reactions, and compositions within a narrow range. Using the Canadian Soil Taxonomy key, the order, Organic Soils, is differentiated at the highest level on the basis of organic content. Organic Soils are divided into four great groups, three of which represent organic soils formed under waterlogging conditions with the fourth representing organic soils formed in upland (folic) organic materials and are soils that are only briefly saturated with water. The criteria for divisions into great group, subgroup, family and series are summarised in Table 2.4.

Table 2.4

Canadian Soil Classification classes and differentiae for the organic order (Soil Classification Working Group 1998)

Great Group	*Subgroup*	*Family*	*Series*
Fibrisol	Typic Fibrisol Mesic Fibrisol Humic Fibrisol Limnic Fibrisol Cumulic Fibrisol Terric Fibrisol Terric Mesic Fibrisol Terric Humic Fibrisol Hydric Fibrisol	Characteristics of surface tier • Organic surface tier; fennic, silvic, sphagnic (each used only for fibric surface tiers), mesic, humic. • Mineral surface tier, 15-40 cm thick; sandy, coarse-loamy, coarse-silty, fine-loamy, fine-silty, clayey.	Material composition: botanical origin of fibres and nature of ferric layer, if any Thickness, amount of decomposition and relative arrangement of layers
Mesisol	Typic Mesisol Fibric Mesisol Humic Mesisol Limnic Mesisol Cumulic Mesisol Terric Mesisol Terric Fibric Mesisol Terric Humic Mesisol Hydric Mesisol	Reaction classes pH • Euic > 4.5 • Dysic < 4.5 Soil climate classes and subclasses of organic soils • extremely cold to mild • aqueous to arid	Abundance of woody material, logs and stumps. Calcareousness Bulk density Mineral content of organic material
Humisol	Typic Humisol Fibric Humisol Mesic Humisol Limnic Humisol Cumulic Humisol Terric Humisol Terric Fibric Humisol Terric Mesic Humisol Hydric Humisol	Particle-size classes of ferric layer • fragmental, sandy, sandy-skeletal, loamy, loamy-skeletal, clayey, and clayey-skeletal Limnic layer classes • marl, diatomaceous earth, and coprogenous earth.	Soil development in the ferric layer Mineralogy of ferric or cumulic layers
Folisol	Hemic Folisol Humic Folisol Lignic Folisol Histic Folisol	Depth classes(lithic or cryic) • extremely shallow 10-40 cm • very shallow 40-60 cm • shallow 60-160 cm	Texture of ferric or cumulic layers Reaction (pH)

Organic Soils under the Canadian Soil Taxonomy are defined as soils that contain more than 17% organic C (30% or more organic matter) by weight and meet the following specifications.

For organic materials (O) that are commonly saturated with water and consist mainly of mosses, sedges, or other hydrophytic vegetation the specifications are as follows:

1. If the surface layer consists of fibric organic material with or without mesic or humic Op horizons thinner than 15 cm, the organic material must extend to a depth of at least 60 cm.
2. If the surface layer is mesic or humic, the organic material must extend to a depth of at least 40 cm.
3. If a lithic contact occurs at a depth shallower than 40 cm, the organic material must extend to a depth of at least 10 cm. Mineral material less than 10 cm thick may overlie the lithic contact, but the organic material must be more than twice the thickness of the mineral layer.
4. The organic soil may have a mineral layer thinner than 40 cm on the surface provided that the underlying organic material is at least 40 cm thick.
5. Mineral layers thinner than 40 cm that begin within a depth of 40 cm from the surface may occur within an organic soil. A mineral layer or layers with a combined thickness of less than 40 cm may occur within the upper 80 cm.

For folic materials (L, F. and H) not usually saturated with water there must be

1. Forty centimetres or more of folic materials if directly overlying mineral soil or peat materials.
2. Greater than 10 cm of folic materials if directly overlying a lithic contact or fragmental materials.
3. More than twice the thickness of a mineral soil layer if the mineral layer-is less than 20 cm thick.

In the Canadian Soil Classification system, a control layer is required in order to identify the differentiae relevant to the particular pedon. The control layer is not uniform across the classes and also across the Great Groups, mostly due to the effect of the extremely low bulk density values for organic soils produced by accumulating *Sphagnum* species. The control section (160 cm) for Fibrisol, Mesisol, and Humisol great groups is divided into three tiers: surface (0-40 cm); middle (40-120 cm); and bottom (120-160 cm). Classification at the great group level is based primarily on properties of the middle tier.

2.2.4 New Zealand Soil Classification (Hewitt 1998)

The New Zealand Soil Classification was intended as a national soil classification to replace the New Zealand Genetic Soil Classification and to therefore provide a system which would deliver precise definitions of classes and keys for soil recognition (Hewitt 1998). A hierarchical classification was produced with ascending levels of generalisation, with the grouping of soils into classes based on the similarity of measurable soil properties. The principles laid out in the system assert that the differentiae should be based on quantifiable or observable soil properties, rather than presumed genesis, but consistency with successful parts of the New Zealand Genetic Classification should be maintained. Diagnostic horizons and differentiae are provided, although organic and mineral soil horizons and differentiae are not separated for consideration as in Soil Taxonomy and WRB. The definition of lithic contact is revised for New Zealand, as joints in rocks often occur at interval of less than 100 mm.

The highest division produces Organic Soils which are defined as soils that have horizons that consist of organic soil material (including soils that have skeletal layers in which the matrix of the gravel consists of organic soil material) that within 60 cm of the soil surface are either

1. 30 cm or more thick (cumulative) and are entirely formed from peat or other organic soil materials that have accumulated under wet conditions (they are saturated with water for at least 30 consecutive days in most years, or have been artificially drained) (O horizons), or
2. 40 cm or more thick and are formed from partly decomposed or well decomposed litter (F and H horizons)

Table 2.5

Organic Soils classes under the New Zealand Soil Classification (Hewitt 1998).

Group	***Subgroup***
Litter	Buried-podzol Buried-gleyed Orthic
Fibric	Sphagnic Acid Mellow
Mesic	Acid Mellow
Humic	Acid Mellow

Organic soil material is defined as having at least 18% organic carbon (dry weight basis) and is defined in the New Zealand classification system using morphology and simple analyses for ease of recognition as follows:

Organic soil material has either

1. All of the following:
   a. Colour value moist of 3 or less (after exposure to air) and colour value dry of 4 or less, *and*
   b. Deformable failure, *and*
   c. Weight loss of 65% or more by oven-drying a field saturated sample;

   or

2. More than 20% (by volume) unrubbed fibre content

   or

3. More than 35% (by weight) loss on ignition except in materials dominated by allophanic soil or by limestone.

or

18% or more total carbon

Organic soils are classified into group and sub-group levels as displayed in Table 2.5. Family and Series are not discussed in the classification and differentiae for organic soils are not mentioned, although reference to and correlation with the Soil Taxonomy are mentioned throughout, with a clear move towards the use of Soil Taxonomy as the model system, but with adjustments to account for unique New Zealand soil properties. Soil descriptions for New Zealand soils follow Milne *et al.* (1991), with the primary focus being on land use capability.

2.2.5 Australian Soil Classification (Isbell 2002)

The Australian Soil Classification is multi-categoric, with different levels of generalisation, defining classes on the basis of diagnostic horizons or materials and their arrangement in vertical sequence (Isbell 2002). Classes are based on real soil bodies, and are mutually exclusives with the possible allocation of new soil individuals to classes by means of a key. The guiding principles of the classification are that it should be general purpose, based on Australian soil data as far as possible, with definitions compatible with international classification schemes, as far as practicable. Unlike Soil Taxonomy, there is no depth restriction to the consideration of the soil body and the soil profile under consideration should follow the definition of pedologic organisation provided by McDonald *et al.* (1990) which is: "All soil material resulting from the effect of the physical, chemical and biological processes that are involved in the soil formation." It was also stated that the classification is based on what is there, rather than what may have been present before human disturbance and that the classification gives emphasis on stable attributes as differentiae. The diagnostic horizons and materials follow McDonald *et al.* (1990) or a glossary provided under the classification. Both mineral and organic soil attributes are considered together. No control section is provided for.

The assignation of classes in the classification is carried out through the use of a key, with the highest level being that of order, followed by suborder, great group, subgroup, family, then series. The initial division is that of anthroposol, organosol, rudosol, tenosol, podosol, vertosol, hydrosol, kurosol, sodosol, chromosol, calcarosol, ferrosol, dermosol and kandosols. An organosol is defined as:

Soils that are not regularly inundated by saline tidal waters and either:

1. Have more than 0.4 m of organic materials within the upper 0.8 m. The required thickness may either extend down from the surface or be taken cumulatively within the upper 0.8 m; or
2. Have organic materials extending from the surface to a minimum depth of 0.1m; these either directly overlie rock or other hard layers, partially weathered or decomposed rock or saprolite, or overlie fragmented material such as gravel, cobbles or stones in which the interstices are filled or partially filled with organic material. In some soils there may be layers of humose and/or melacic horizon material underlying the organic materials and overlying the substrate.

Organic materials are defined following Soil Taxonomy (Soil Survey Staff 1998), as plant-derived organic accumulations that are either:

1 saturated with water for long periods or are artificially drained and, excluding live plant tissue, i) have 18% or more organic carbon if the mineral fraction is 60% or more clay, ii) have 12% or more organic carbon if the mineral fraction has no clay, or iii) have a proportional content of organic carbon between 12 and 18% if the clay content of the mineral fraction is between zero and 60%; or

2 saturated with water for no more than a few days and have 20% or more organic carbon.

Although the classification for oganosols closely follows Soil Taxonomy (see Table 2.6), folic is in the great group class. This is equivalent to folist in the suborder class in Soil Taxonomy (Soil Survey Staff 2006).

The minimum depth for an organosol is 10 cm. Shallower organic-rich soils would come under the order, tenosol, and would most probably belong to the suborder chernic-leptic, the great group lithic or paralithic, the subgroup peaty, humose-acidic or humose, with family criteria based on thickness, gravel content or texture.

Table 2.6

Australian Soil Classes for the order organosol (Isbell 2002).

Suborder	*Great Group*	*SubGroup*	*Family*
Fibric	Folic	Lithic	*Nature of uppermost organic material*
Hemic	Sulfuric	Paralithic	granular
	Sulfudic	Marly	
	Calcareous	Rudaceous	*Thickness*
	Basic	Modic	very thin to giant
	Acidic	Placic	
Sapric		Ashy	
		Terric	
		Regolithic	

2.2.6 English and Welsh Soil Classification (Avery 1980)

The soils of England and Wales are also classified under a hierarchical system, differentiated by observable or measurable characteristics of the soil profile. There is a depth restriction, similar to that in Soil Taxonomy which defines the depth of consideration as extending from the ground surface to about 1.5 m, even though the classification is intended for surveys of both cultivated and uncultivated land. The profile characteristics used to classify soils are divided into characteristics inherited from the soil parent material and characteristics resulting from alteration of the original parent material by soil-forming (pedogenic) processes and expressed as distinctive surface and subsurface horizons. Soil profile characteristics are used to define soils at five levels in a hierarchical system (order, major group, group, subgroup, and series) with general characteristics being used at the highest level to give broad separations with lower level differentiae increasingly precise. At major group level, divisions are based on the predominant pedogenic characteristics of the soil profile. Soil groups and subgroups are subdivisons based on features which further define the inherent characteristics of the soil material, or modify the basic pedogenic characteristics recognised at major group level. A soil series, the lowest category in the system, is a subdivision of a subgroup based on precisely defined particle-size subgroups, parent material (substrate) type, colour and mineralogical characteristics (Avery 1980, Clayden and Hollis 1984).

Horizon designations and differentiae are considered separately for organic and mineral soils. Horizon designations for organic soils serve purely to define the minimum depth limit with the organic soils differentiae providing for classification for both subgroup and series classes as summarised in Table 2.7. Soils that may correlate with the histosols of Soil Taxonomy and WRB and organosols of the Australian Soil Classification are summarised in Table 2.7.

Table 2.7

The English and Welsh Soil Classification classes and differentiae (Avery 1980).

Major Groups	***Groups***	***Subgroups***	***Series***
Lithomorphic Soils	Rankers	Humic	Dominant particle size class (normally upper 80 cm) Presence and nature of texturally contrasting layers, bedrock or horizons impenetrable to roots within a specified depth Origin of soil material Mineralogy or related characteristics
Peat Soils	Raw	oligo-fibrous	Botanical origin and degree of composition of fibrous sub-surface layers, and mineral-matter content of humic or limnic layers Presence and composition of mineral substrata within a specified depth Presence of a humilluvic layer
		oligo-amorphous	
	Earthy	oligo-fibrous	
		eu-fibrous	
		eutro-amorphous	
		Sulphuric	

Organic soil materials are either:

1. Seldom saturated with water for more than a month at a time and have 20% or more organic carbon (35% organic matter).
2. Saturated with water for longer periods or artificially drained and have more than 18% organic carbon (30%) organic matter) if the < 2 mm inorganic fraction is 50% or more clay, more than 12 % organic carbon (20%) organic matter) if there is no clay, and proportionate organic carbon contents with intermediate clay values.

The first criterion is described as L, F, H organic accumulations, and the second criterion is described as peat and is designated the letter O. Peat is further divided into fibrous (fibric), semi-fibrous (mesic or hemic) or amorphous (humic or sapric), with correlations with other taxonomies given in brackets.

Peat soils are required to have organic materials at least 40 cm thick, starting at the surface, or at least 30 cm depth. Other soils, including those with a thinner organic layer resting more or less on hard rock or fragmented material, are considered mineral soils.

As many Tasmanian organic soils do not meet the depth requirement for an organic soil under the English and Welsh Classification System, the mineral soil correlates of the Australian organosol are provided in Table 2.7 as lithomorphic soils. The major group, lithomorphic soils, are defined as having a distinct humose or peaty topsoil with a little-altered mineral substratum (normally C or bedrock) starting at or within 40 cm depth; no diagnostic weathered, argillic or podzolic B horizon; no gleyed sub-surface horizon unless extremely calcareous; no disturbed sub-surface layer. The lithomorphic group, Rankers are defined as non-calcareous lithomorphic soils, usually having bedrock or skeletal material within 40 cm depth with the subgroup, humic rankers, having a humose or peaty topsoil.

2.2.7 Conclusion

All the major soil classifications require an soil organic carbon content of over 12% organic carbon and a minimum depth of 0.3 - 0.4 m for an organic soil, with some classifications requiring a higher organic carbon content but shallower depth requirement (0.1 m) for folic organic sols. In all the classifications, the initial division of organic soils is related to the humification of the organic soil, including, or in the Australian Soil Classification, followed by, the water table regime. Differentiae further used in classifications include nutrient status of the organic soil, acidity, dominant vegetation, climate and the nature of the underlying substrate, often for purposes that may not be relevant to the conservation use of the majority of Tasmanian organic soils. For example, the ability of the underlying substrate to be broken by blasting or heavy machinery for engineering purposes was the main purpose behind differentiating between lithic and paralithic contact in Soil Taxonomy (Brasfield 1984). This differentiation has since been used in several other classifications. Some classification systems provide for a control section to which the differentiae are applied and also provide for a separate consideration of horizon properties for organic soils and mineral soils. The similarities and differences in treatment of organic soils in these classification systems are a reflection of borrowed terms and definitions and nationally specific differentiae. As most of the work on organic soils has been based on Northern Hemisphere soils and has been directed to their use in agriculture, it is suspected that the differentiae in existence for the Australian Soil Classification may not truly reflect the dominant gradients and differentiating factors for Tasmanian organic soils. While it may be difficult to depart from the internationally-recognised primary taxonomic division of humification classes, additional differentiae might reflect dominant characteristics relevant to Tasmanian organic soils.

2.2 Landform classification relating to organic soils

Soil taxonomy and classification arose from land capability classification for agriculture and forestry, with less importance placed on the careful classification of uncultivated and uncultivatable soils. This has led to organic soils being defined and described in terms of landform features, with a body of research attempting both national and international genetic classifications. As yet, there is no international consensus on terminology and, hence, no international classification for organic soil landforms, with the lack of agreement largely due to the existence of well-accepted national systems that are too localised to be internationally transferable. A number of terms associated with organic soil landforms and a few regional classifications are reviewed.

Systems of landform classification for soil mapping have been developed in the USA, Canada (Soil Classification Working Group 1998) and Australia (McDonald *et al.* 1990) and are intended as field classification systems whereby basic attributes are recognised in terms of their inherent properties rather than on their inferred genesis. The systems apply to "local" landforms that are readily represented on maps at scales of 1:50,000 to 1:500 000.

To highlight the problems experienced in using landform classifications in describing, or at least as an aid in describing the genesis of organic soils, the following extract has been taken directly from the International Mires Conservation Group's (IMCG) Wise Use of Peatlands Handbook (2002):

"Every international approach in peatland science and policy is complicated by the multitude of terms, the inconsistencies in their definition, and the different concepts behind similar terms in different languages and disciplines (Overbeck 1975, Fuchsman 1980, Andrejko *et al.* 1983, Zoltai and Martikainen 1996). Multilingual lexicons and their precursors (e.g. Früh and Schröter 1904, Masing 1972, Overbeck 1975, Gore 1983) have paid too little attention to this problem. Many concepts have further been confused by uncritical translation of terms, even in translations of important handbooks (Joosten 1995). Some illustrations: the English "moor", the German "Moor", the Dutch "moer", the Swedish "myr" and the English "mire" do not have the same meaning and cannot be (but too often are...) translated one into the other. The same accounts for the German "Torf", the English "turf" and the Dutch "turf", although the meaning of the latter is somewhat similar to that of the Irish "turf". In one and the same language, the meaning of words is ambiguous and may change in time (cf. Wheeler and Proctor 2000) or may differ from discipline to discipline. In some languages the words commonly used for the type of landscapes we want to discuss do not differentiate between areas with and without peat (cf. the English "moor", the French "fagne" and "marais", the Finnish "suo", the Russian "(boloto)", the Georgian "tsjaowbi"), between peat forming or not peat forming (cf. the German "Moor", the Dutch "veen", the English "bog" and "fen"), or only indicate the presence of an economically extractable volume of peat (cf. "tourbière", "torfeira", "turbera" in Romance languages)."

Terminology was further reviewed, discussed and changes suggested in Wheeler and Proctor (2000). The changes posed by Wheeler and Proctor (2000) were rejected by Øklund *et al.* (2001) for Scandinavian peatland systems. The most likely source of an internationally agreed upon terminology will probably be by direction from the IMCG. Despite the inconsistencies in terminology, a selection of the definitions is provided in Table 2.9.

Table 2.9

Definitions of landform terms.

Peat

"A substance composed of the partially decomposed remains of plants with over 65% organic matter (dry weight basis) and less than 20-35% inorganic content" (Clymo 1983, Heathwaite *et al.* 1993). "Peat is sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material"(IMCG 2002).

Peatland

"Any ecosystem where in excess of 30-40 cm of peat has formed. This includes some wetlands, but also organic soils where aquatic processes may not be operating (e.g. drained or afforested peatlands)" (Charman 2002). "A peatland is an area with or without vegetation with a naturally accumulated peat layer at the surface. To provide a uniform standard, the data with respect to peatlands – unless stated otherwise - concern peatlands with a minimum peat depth of 30 cm. The criterion "minimum peat depth of 30 cm" excludes many (sub) arctic and (sub)alpine areas with a shallow peat layer "(IMCG 2002).

Suo

"A wetland with or without a peat layer dominated by vegetation that may produce peat. Areas with a peat depth > 0 cm and < 30 cm are listed under 'suo'" (IMCG 2002).

Mire

All ecosystems described in English as swamp, bog, fen, moor, muskeg and peatland (Gore 1983), but often used synonymously with peatlands (Heathwaite *et al.* 1993), especially in Europe (Tarnocai 1998, Warner 2001). "All natural and semi-natural peat communities with their peat substratum, embracing both bog and fen" (Godwin 1941). Has also been restricted to those wetland systems where peat accumulates (Moore and Bellamy 1974) and is actively accumulating (IMCG 2002). Wheeler and Proctor (2000) recommend the definition of Mörnsjö (1969) for mire which would be a permanent telmatic wetland.

Bog

A bog has been defined as a mire receiving exclusively ombrogenous water resulting in acidic peats with associated indicator vegetation (Sjörs 1948, Malmer 1962, Fransson 1972, Tarnocai 1998, Charman 2002, IMCG 2002).

Fen

A mire which is influenced by water from outside its own limits; geogenous water resulting in weakly acidic to alkaline with associated indicator vegetation (Sjörs 1948, Malmer 1962, Fransson 1972, Tarnocai 1998, Charman 2002).

Marsh

"Permanently or periodically inundated site characterised by nutrient-rich water" (Tarnocai 1998). "A fen with tall herbaceous vegetation often with a mineral substrate"(Charman 2002).

Swamp

"Forest peat covered or forest peat-filled areas where the water table is at or above the peat surface. The dominant peat materials are shallow to deep mesic to humic forest and fen peat formed in a eutrophic environment resulting from strong water movement from the margins or other mineral sources" (Tarnocai 1998)

Landform peatland classifications have been based on the following factors which are given a brief overview with regard to their possible relevance to Tasmanian organic soil landforms. From research in the Northern Hemisphere, great emphasis has been placed on the source of water supply and therefore acitity and nutrient status in classifying peatlands. It has been found in many Northern Hemisphere studies (Weber 1902, Du Rietz 1949, Sjörs 1948, 1950, 1952, Malmer 1962, 1985, 1986, Økland 1989), that a gradient exists from geogenous, alkaline water (fens) to ombrogenous, acidic water (bogs). Northern Hemisphere peatlands have been, therefore, generally divided into classes along a continuum between ombrogenous and geogenous mires (Kulczyński 1949, Moore and Bellamy 1974), reflecting the source of water supply to the peatland system, and the acidity gradient. The acidity gradient has been well developed and used in the Northern Hemisphere peat (Sjörs 1948, Du Rietz 1949, Malmer 1962, 1985, 1986), also indicated by changes in vegetation (Sjörs 1948, Du Rietz 1949, Malmer 1962, 1985, 1986, Gignac and Vitt 1990, Vitt 1994, Halsey *et al.* 1997, Mitch and Gosselink 2000). Ombrogenous peatlands, which include the landforms raised or blanket bogs, are mostly acidic, receiving water and nutrients solely from the atmosphere through direct precipitation, with ground water and runoff from surrounding land not affecting the surface of the peatland. Rain and snow provide the water source, and nutrients are derived from atmospheric deposition in the form of rainfall, ash, dust and animal detritus, and therefore, with limited nutrients available for plant growth, specialist plants, such as

Sphagnum species, are characteristic. Divisions of ombrogenous peatlands according to acidity gradients have been suggested (Bridgham *et al.* 1996, Økland *et al.* 2001) to represent stages along the gradient from bog to the mire margin. Geogenous peatlands include the landforms, fen, which receives surface runoff and/or ground-water recharge from surrounding mineral-soil sources. In the Northern Hemisphere fens, nutrients from geogenous water sources have been deemed more abundant and water more alkaline than ombrogenous sources of water (Wheeler and Proctor 2000). Fens are further classed according to their acidity status from acidic through neutral to alkaline, with associated vegetation (Sjörs 1948, Du Rietz 1949, Fransson 1972, Vitt 1994, Halsey *et al.* 1997, Økland *et al.* 2001).

Classification of mire types has been based on vegetation on the surface, as well as the vegetation composition of the peat (Cajander 1913, Tsinserling 1938, Katz 1948, 1971, Ruuhijärvi 1960, Eurola 1962, Sarasto 1961, Tolpa *et al.* 1967, Daniels *et al.* 1971, Rowe 1972, Jeglum *et al.* 1974, Cowardin *et al.* 1979, Dierssen 1979, Dobson 1979, Eurola and Kaakinen 1979, Smith 1979, Zoltai *et al.* 1988) and the underlying stratigraphic vegetation remains (Auer 1965, Walker 1970). The species composition of the plant communities is often used as a proxy measure of other criteria such as chemistry and hydrology, and mixed classifications, based on floristics and a combination of other factors, but especially chemical composition of the mire waters and water regime, have been developed (Osvald 1923, Kotilainen 1927, Kivinen 1935, Multamaki 1936, Katz 1948, Kulczyński 1949, Malmer 1962, Moore 1968, Jensen 1972, Damman 1995, Økland *et al.* 2000).

The three dimensional shape of the peat deposit itself and of smaller scale features on its surface have also been used to classify mires using macro to micro scale geomorphological features to provide the identifying characteristics (Moore and Bellamy 1974, Ivanov 1981, Zoltai 1988), which are further used to provide a hydroseral classification from primary mires through secondary mires to tertiary mires (Moore and Bellamy 1974). Radforth (1977) developed a purely geomorphological classification based on the topographic setting of mires, with confined mires restricted to topographic basins and unconfined mires covering the landscape, with the exception of very steep slopes, and partly confined mires an intermediate between confined and unconfined.

The source and flow regime of the water supply of both surface and groundwater has been used to typify mires in relation to the condition of mire initiation (von Post 1922, von Post and Granlund 1926) with the division between ombrogenous and geogenous peatlands, referring to the source of water giving rise to the organic accumulation (Kulczyński 1949, Zoltai *et al.* 1975, Okruszko 1977). Additional definitions of geogenous that have been used include topogenous (Von Post 1926, Sjörs 1948) soligenous and limnogenous (Katz 1948, Eurola and Kaatinen 1979). Goode and Ratcliffe (1977) described mires using a hydrotopographic typology using terms such as raised mire, blanket mire, basin mire, valley mire, flood plain mire, open water transition mire and soligenous mire with these terms being used and refined since (Goode and Lindsay 1979, Masing 1982, Moen 1985, Damman and French 1987, Lindsay *et al.* 1988, Charman 1993, Lindsay 1995). A hydrogenetic mire typology has been developed by Succow (1998), Succow and Joosten (2001), and Jeschke and Succow (2004) with emphasis on the relationship between water supply, mire evolution and nutrient budget. Fifteen hydrogenetic mire types have been identified (Jeschke and Succow 2004); paludification mire, groundwater paludification mire, surface water damming mire, sloping mire, terrestrialisation mire, spring mire, fluvial and coastal transgression mires, percolating mire, kettle mire, ombrogenous mire, peak mire, saddle mire, valley mire and ombrogenous trickle flow mire.

Peat and peatlands have also been characterised for their uses, especially for forestry (Toleman 1973, Pyatt *et al.* 2001), agriculture (Lukkala and Kotilainen 1951, Heikurainen 1955, Davoren 1978), horticulture (Farnham and Finney 1966, Barry 1979), fuel (CENT/TS 14961 2005), engineering (Radforth 1959, 1969) and land use for building (Healey 1978).

Charman (2002) suggests that the hydromorphological classification is probably the only universally applicable system where the overall shape of the peat deposit and the underlying ground, together with a basic idea of the site hydrology, to provide a set of basic types which are then subdivided on the basis of a more detailed understanding of their vegetation, water chemistry and peat stratigraphy. The basic types are shown in Figure 2.1, taken from Charman (2002).

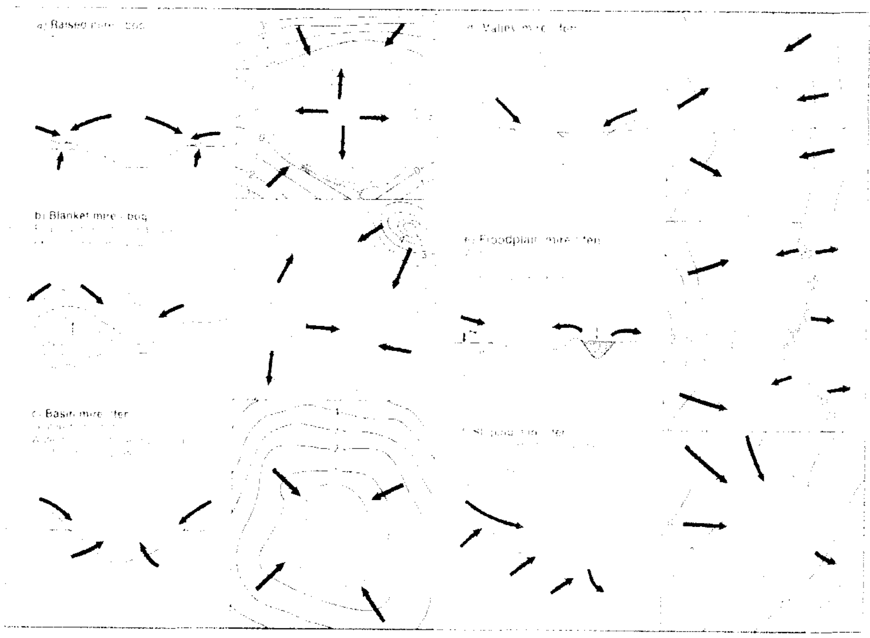

Figure 2.1

Schematic cross-sections and plan views of key hydromorphological mire types. Source: Charman (2002).

There has been no unified attempt to categorise organic soil landforms in Australia, let alone Tasmania, although the term blanket bog has been used often (Jarman e*t al.* 1988, Pemberton 1989). The terms string bog and string fen (Kirkpatrick and Gibson 1984, Whinam and Kirkpatrick 1994) have also been used. The use of these terms and possible correlates with other terms in use, with respect to Tasmanian organic soil producing landforms, will be assessed in Chapter 7. As there is no internationally agreed upon classification system for organic soil producing landforms, possible correlates with Tasmanian systems can only be based on the over-riding themes underlying these attempted classifications which have so far been based on dominant ecological gradients and hydrological genesis. It is therefore important to describe the soils before attempting to place them in a landform classification.

2.3 Conclusion

In order to predict, locate and map organic soils in Tasmania, it is necessary to assess and characterise the nature of the existing organic-rich soils. As it is surmised that the majority of the organic soils are under reserved land, the dominant aim of classification and characterisation of these soils is to provide for the land use under which the greatest areal extent of organic soil is found. It is believed that classification for inventory and soil organic carbon stock assessment are the most important purposes. Biodiversity, geodiversity and fire management are important in the reserved land on which the organic soils occur (PWS 2004). In order to maintain a geographic element to any proposed changes to the Australian Soil Classification, the interplay of soil taxonomic units, genetic units and mapping units in informing the classification is considered. This follows criticisms of Soil Taxonomy's ability to inform soil surveying and mapping of the taxonomic units it produces (Campbell and Edmonds 1984, Young and Hammer 2000). An initial assessment of previous studies on Tasmanian organic soils in relation to the dominant organic soil-forming factors is made, followed by a characterisation of edaphic properties and then the environmental conditions under which organic soils are found. Finally organic soil accumulating processes are considered in informing a predictive model, followed by the production of mapping units.

Chapter 3

Unsupervised cluster classification

3.1 Introduction

The aim of this chapter is to use commonly used soil characteristics to describe the order organosols in Tasmania to produce a finer resolution than is currently available in the Australian Soil Classification. Rather than attempting to fit Tasmanian organic soils to the current Australian Soil Classification (Isbell 2002), a partly independent classification, based on statistical analysis and modelling of commonly used organic soil characteristics using unsupervised clustering techniques is developed. Log-linear modelling is used to define the most influential variables, which are then used to construct a key or decision tree to describe the soil subsets.

3.2 Methods

3.2.1 *Sampling strategy*

3.2.1.1 Initial site selection

Sites were chosen for their possibility of being classed as an organosol under the Australian Soil Classification System (Isbell 2002). A range of both formal and informal sources was used in helping to identify suitable sites. These included Forestry Tasmania data (Brown *et al.* 2002), Fire Management, Department of Primary Industries and Water (DPIW) data (Marsden-Smedley pers. comm.), Nature Conservation, Branch (DPIW) data (Balmer unpub. data, Whinam pers. comm.) and previous publications (Stephens 1962, Nicolls and Dimmock 1965, Jackson 1968, Nicolls 1968, Costin 1972, Stace *et al.* 1972, 1986, Richley 1978, Tarvydas 1978, Brown and Podger 1982, Colhoun *et al.* 1982, Jarman *et al.* 1982, 1984, 1988a, 1991, Kirkpatrick 1982, 1988, Kirkpatrick and Dickinson 1984, Kirkpatrick and Gibson 1984, Kirkpatrick *et al.* 1985, 1997, Pemberton 1986, 1988, 1989, Bowman *et al.* 1986, Davies 1988, Balmer 1990, 1991, Brown *et al.* 1990, 2002, Gibson 1990, Whinam 1990, Pannell 1992, Hannan *et al.* 1993, Grant *et al.* 1995, Hill *et al.* 1995, 1999, Thomas and Kirkpatrick 1996, Bridle and Kirkpatrick 1997, Kirkpatrick and Bridle 1998, Whinam *et al.* 2001). Sites were located, mostly using a 1:25,000 scale map (TASMAP 2000), the largest scale available. Only some of the literature provided enough data to determine whether soils they described met the criteria for classification as an organosol (Nicolls 1957, Bowman *et al.* 1986, Whinam 1990, Thomas and Kirkpatrick 1996, Bridle and Kirkpatrick 1997). It was therefore decided to conduct a systematic sampling of the regions reported in the literature as having organic soil, peat or organic-rich podsols. In order to capture the possible influences on soil–forming processes, the major factors of soil formation (Jenny 1941) and especially organic soil formation (Charman *et al.* 1999) were controlled for: topography (landform), parent material (underlying geology), climate (temperature and moisture) and biological activity (flora) occurring through time (soil age). An initial 157 sites were chosen, throughout Tasmania, with between one and three soil pits dug at each site, based on the areas reported to have peat in the literature. After initial laboratory testing on organic content, not all of these initial sites were found to contain organosols (Figure 3.1).

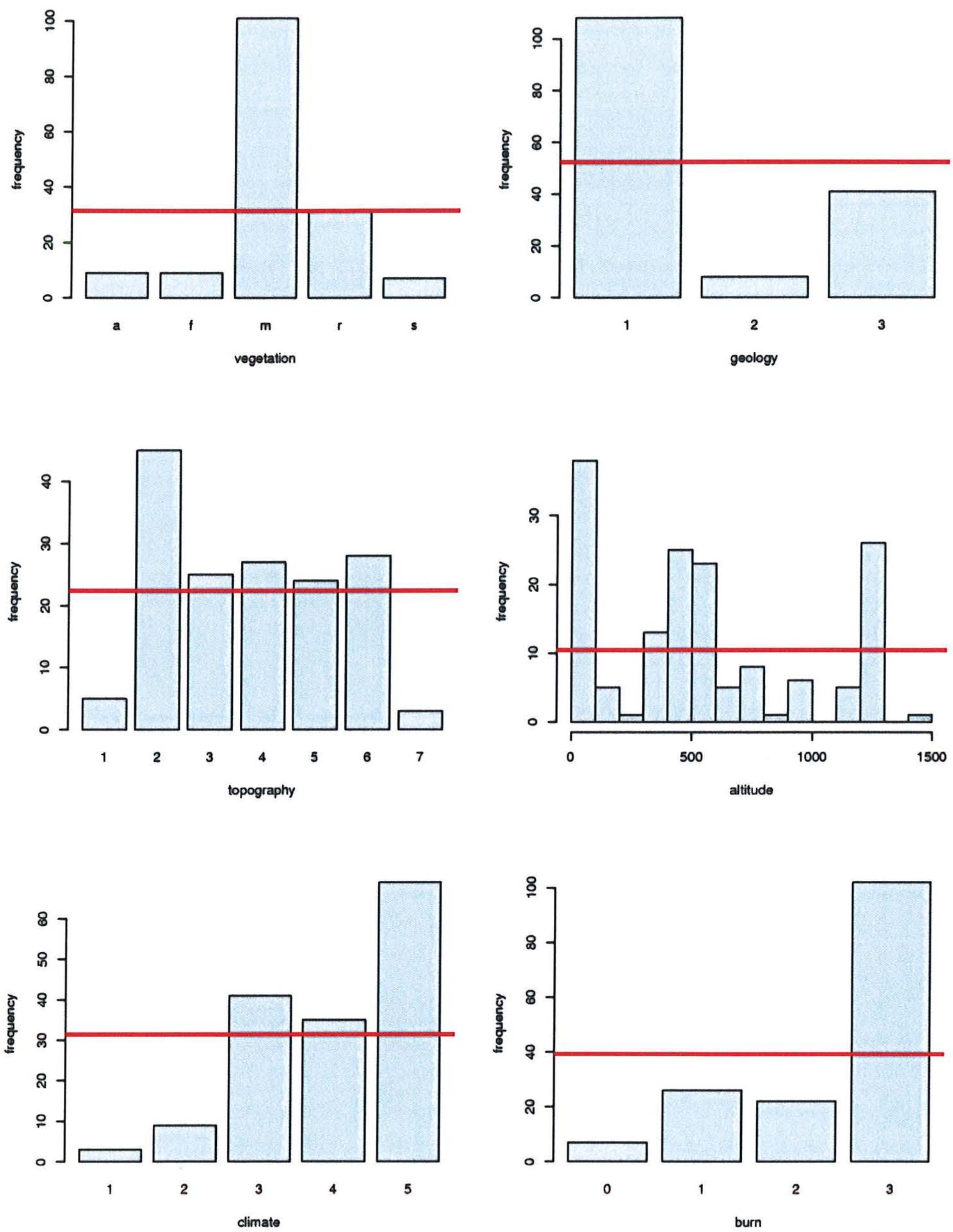

Figure 3.1

Frequency distributions (number of sites, n, on the y axis) of the initial 157 sites with the red line representing an equal distribution of occurrence for each class and the blue bars representing the actual frequency of the occurrence of an organosol for each class. The variables shown on each plot are, from left to right; top to bottom, vegetation (broad vegetation types described in Table 4.1), geology (geology fertility types described in Table 4.3), topography (topography types described in Table 4.2), altitude (in 15 classes of intervals of 100 m a.s.l., climate (5 climate types defined in Appendix 11) and burn frequency (defined below).

3.2.1.2 *Final site selection*

The sampling sites were chosen from those sites found to contain organosols. Of the initial 157 sites, 127 were found to contain organic soils, with the majority of those sites on the Precambrian metamorphosed sediments in the west and south west. A limited number of sites were found on Jurassic dolerite where they were restricted to topographic basins, depressions, springs or flushes, in areas of high rainfall or high ground water levels and low temperatures (Figure 3.1). The sites used for analysis in this chapter are shown in Figure 3.2.

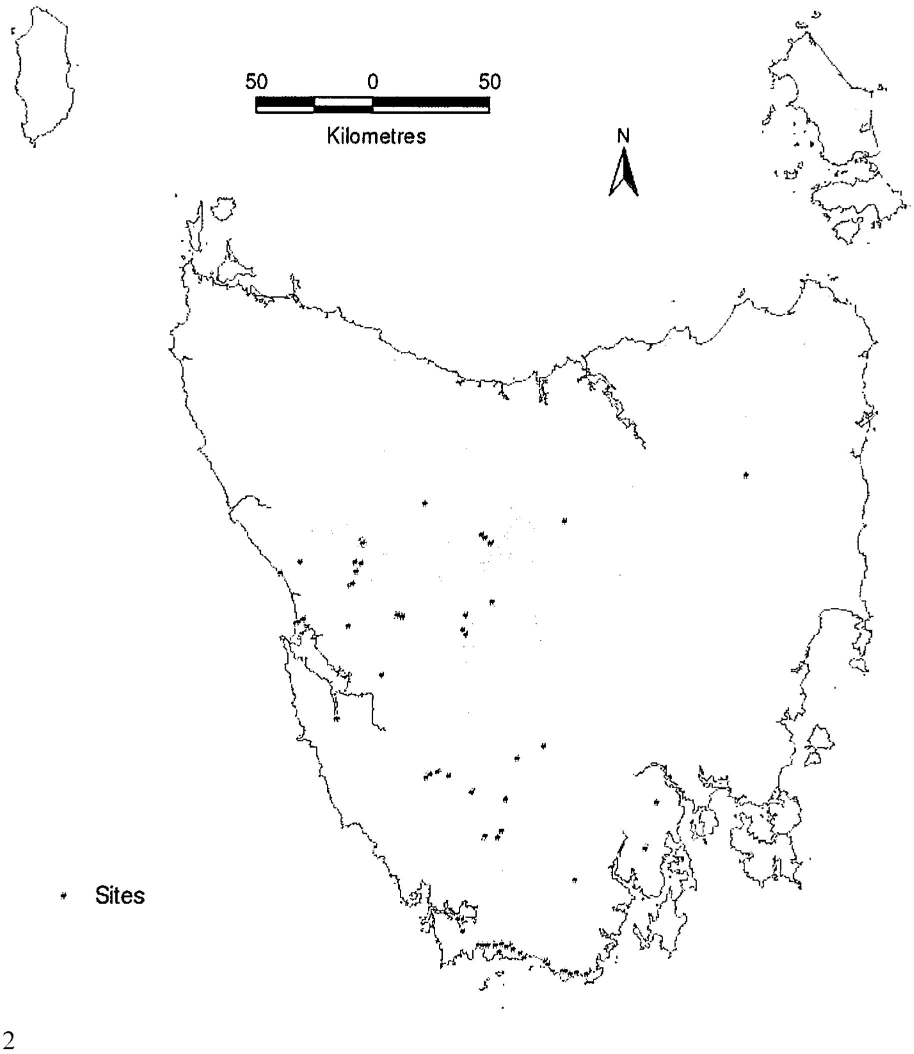

Figure 3.2

Individual sites and site area locations used in the final soil selection.

3.2.1.3 Selection of soil pits within sites

Where a site was found to contain organosols, a stratified random sampling procedure was performed. Sites were divided into floristic, vegetation structure, topographic (and hydrological) and geological units and between 10 and 20 random soil pits were dug within each stratum. The data used in this chapter are for individual soil pits, located at each site using this random, stratified sampling. As far as possible, sites were replicated to control for the organic soil producing factors and a total of 1,159 soil pits were used in the final survey, with replications for each substrate type, broad vegetation type, altitude, climate, and topography. As climate, geology and vegetation type were strong factors in the initial sampling, sites were targeted based on these three factors initially and then controlled for topography once on site. Despite this, it is expected that certain vegetation types may have been overlooked or under-replicated in the sampling due to unsuccessful attempts to locate organic soils. Also, sampling over a range of vegetation was often difficult in alpine regions, due to remoteness. In some instances, when sampling a particular floristic and vegetation mapping unit, much ground had to be covered to find a soil that, visually and texturally, was organic enough to warrant sampling. The soil pits used for analysis are those 1,159 found to contain organosols as defined by Isbell (2002).

3.2.1.4 Soil sampling

As many of the sites were remote and inaccessible, cores could not always be obtained. After the initial survey, it was decided that soil pits would be more appropriate than cores for the soil survey, as they allowed for water table observations and bulk density extraction and did not require the transport of heavy equipment. Where the soil depth was greater than 2 m, a small core was taken using a metal probe. Sampling procedures, replicates and sample bulking followed the suggested Australian standard methods set out in McKenzie *et al.* (2002) for stratified random sampling. A minimum of 10 pits were dug at each site and 100 mm diameter and 300 mm length cores were removed from perceptible horizons. Where no horizons were visible, or discernible through change in texture, equidistant samples were taken every 10 cm from the surface to the total soil depth.

3.2.2 Measurement of soil characteristics

Commonly used soil characteristics were considered in light of the volume, and therefore weight, of soil able to be carried out of remote areas. In defining organosols, organic carbon and depth were necessary (Isbell 2002) and they were therefore measured. Other classification systems reviewed in chapter 2 use bulk density, nitrogen, humification, water table, drainage, pH and colour to classify organic soils. These were also analysed. The codes used for the measured soil characteristics are explained in Appendix 1.

3.2.2.1 Data collection in the field

3.2.2.1.1 Soil depth

Either a 2 m or 4 m long, 5 mm diameter stainless steel probe was used to measure the soil depth where a soil pit could not reach the regolith, rock or mineral soil. The probe could be rotated and used to extract small samples to check the texture, colour and humification of out-of-reach soil horizons.

3.2.2.1.2 Horizons

Soil horizons, as defined for use in Australian soil classifications (McDonald *et al.*, 1990, McKenzie *et al.* 2002, Isbell 2002), were assigned where possible. Separate horizons for consideration were defined by perceptible changes in colour, texture and/or root depth. Organic rich horizons fall within the O and P horizons described by McDonald *et al.* (1990) and mineral horizons were also recorded according to the methods described by McDonald *et al.* (1990). The thickness of each horizon was recorded in the field, along with depth to substrate.

3.2.2.1.3 *Humification*

Each soil horizon was assigned a humification class in the field using the 10 class von Post scale (Von Post, 1922). This was used in preference to the broader classes of fibric, hemic and sapric used in the Canadian (Tarnocai 1998), American (Soil Survey Staff 1999), New Zealand (Hewitt, 1998) and Australian (Isbell, 2002) soil classifications. The conversion from the von Post classes can be made post-classification, if necessary, and should follow Avery (1990) and Isbell (2002).

3.2.2.1.4 *Colour*

Colour was recorded in the field using the Munsell (Munsell Color Chart Company 1975) soil colour chart and following the recommendations of McKenzie *et al.* (2002). In some cases, colour determination was not possible in the field, although colour was described on pre-air-dried soils within a couple of days of collection and while still wet. Only the chroma was used in the classification analysis, as the hue (10 yr) and value (2) did not vary for organic materials. The exception to this was organic soils containing a high percentage of poorly decomposed *Sphagnum* species the colour of which was not represented in the Munsell Chart. They were given a NA value in the data set.

3.2.2.1.5 *Watertable depth*

Watertable depth was measured in cm at the time of sampling, although at some sites, sampling was repeated over 2 years after various rainfall events and during drought conditions. These sites were part of a fire regime – organic soil interaction experiment. A relationship has been found between watertable depth and humification (see Appendix 2). Where repeated measurements were not possible, humification was taken as a surrogate measure. At some sites electrical taping was wound around steel pins which were fixed in the soil. The tape discoloured in relation to the saturation of the soil and this discoloration was used as a measure of water table range (Belyea 1999, Navrátilová and Hájek 2005). Due to the variable accuracy in these data, it was only possible to assign the profiles to 6 water table classes using a method described by McDonald *et al.* (1990). This is described as "drainage" in the handbook and the classes are summarised as follows:

"1 *very poorly drained* - water is removed from the soil so slowly that the water table remains at or near the surface for most of the year.

2 *poorly drained* - water is removed very slowly in relation to supply. Seasonal ponding resulting from run-on and insufficient outfall also occurs. A perched water table may be present. All horizons remain wet for periods of several months

3 *imperfectly drained* - water is removed only slowly in relation to supply. Horizons remain wet for several weeks.

4 *moderately well drained* - water is removed from the soil somewhat slowly in relation to supply, due to low permeablility, shallow water table, lack of gradient, or some combination of these. Some horizons remain wet for several days after water addition.

5 *well drained* - water is removed from the soil readily, but not rapidly. Excess water flows downward readily into underlying moderately permeable material or laterally as subsurface flow. Some soil horizons may remain wet for several days after water addition.

6 *rapidly drained* - water is removed from the soil rapidly in relation to supply. Excess water flows downward rapidly if underlying material is highly permeable. There may be rapid subsurface lateral flow during heavy rainfall, provided there is a steep gradient. No horizon is normally wet for more than several hours after water addition."

3.2.2.1.6 Permeability

Permeability was assessed in the field according to the classes described in the Australian Soil and Land Field Survey Handbook (McDonald *et al.* 1990) method of assessing internal drainage (permeability) on a scale of 1-3. It was found that 5 classes could be discriminated. The classes are as follows:

"1 *slowly permeable* - the potential to transmit water vertically is so slow that the horizon or soil would remain wet (saturated) for periods of a week or more after thorough wetting, whether or not there were obstructions to water movement outside the soil body. The soil may vary in structure, but there are few pores that could conduct water when the soil is wet; cracks or spaces among peds that may be present when the soil is dry, close on wetting.

2 *moderate to slowly permeable* - this class is between class 1 and 3

3 *moderately permeable* - the capacity to transmit water vertically is such that the soil would remain wet for no more than a few days after thorough saturation if there were no obstructions to water transmission outside the soil body. Soil horizons may vary in structure, or they may be massive (but porous) if they contain continuous conducting pores or cracks that do not close with wetting.

4 *moderately to highly permeable* - this class is between class 3 and 5

5 *highly permeable* - the capacity to transmit water vertically is so great that the soil would remain wet for no more than a few hours if there were no obstructions to the water movement outside the soil body. The horizons have large and continuous or connecting pores that do not close with wetting."

Where field observations were not taken in remote areas, the same permeability classes were assigned using a technique described in McKenzie *et al.* (2002) which involved dripping a known volume of water over a partially contained sample, sitting on top of a steel mesh, and timing the passage of water through the soil sample, adjusting also for depth.

3.2.2.2 Soil laboratory analyses

All samples were air dried as soon as possible after collection. The samples were then passed through a 2 mm aperture sieve prior to analysis. Large roots were withheld.

3.2.2.2.1 Organic matter

Organic matter was measured as percentage weight loss from fired oven dry soil (loss on ignition). Moisture was removed from the samples through oven drying at 105°C until the weight was constant (usually within 24 hours). The samples were then immediately processed and fired at 550°C for 6 hours. The firing temperature and duration was experimented with initially, using referenced methods of higher and lower temperatures (ranging from 450°C to 600°C) and longer and shorter firing times (ranging between 1 hour and 8 hours). Previous research has found firing at 550°C for 6 hours to give the most easily replicated results (Ball 1964, Heiri *et al.* 2001, Isbell 2002, Boyle 2004) and gave comparable results to other variations of duration and temperatures.

3.2.2.2.2 Organic carbon

Loss on ignition is used here as an estimate of organic carbon according to the methods used in Isbell (2002) for use in defining Australian organosols. The presence of clay was identified through standard bolus rolling techniques (McDonald *et al.* 1990). These samples were sieved and the percent clay was calculated to determine the relevant factor to use in converting loss on ignition to organic carbon.

The conversions given in Isbell (2002) are:

when clay is	*Clay (%)*	*Organic carbon*
	< 20%	LOI (loss-on-ignition) / 2.0
	20 – 60%	LOI (loss-on-ignition) / 2.3
	> 60%	LOI (loss-on-ignition) / 2.7

Other soil classification systems use a factor of 1.724, regardless of clay content (Soil Survey Staff 1996).

3.2.2.2.3 *Total organic carbon*

The method for determining total organic carbon follows the Australian Laboratory Handbook of Soil and Water Chemical Methods (Rayment and Higginson 1992) which is recommended for Australian soil survey and classification by McKenzie *et al.* (2002) and Isbell (2002). The Heanes wet oxidation method for non-saline soils was conducted on an air dried sample (< 2 mm). The total organic carbon is expressed as percent total organic carbon on an oven dry basis. The inorganic carbon value was subtracted, where necessary. Inorganic carbon, representing maximum carbonate content, was calculated from an acid neutralisation titration using the method described by McKenzie et al. (2002).

3.2.2.2.4 *Total Kjeldahl nitrogen*

The method for determining total Kjeldahl nitrogen follows Rayment and Higginson (1992), which is the method recommended by Isbell (2002). Total nitrogen was determined on air dried samples, passed through a < 2 mm aperture sieve, using the semimicro Kjeldahl, steam distillation wet oxidation method and is expressed in percent total nitrogen of the oven dry soil sample. Total Kjeldahl Nitrogen quantifies the amount of total nitrogen plus ammonia/ammonium nitrogen.

3.2.2.2.5 *pH*

The pH of samples was determined following the directions and methods of the Australian Laboratory Handbook of Soil and Water Chemical Methods (Rayment and Higginson 1992). The soil pH procedure was performed on an air dried sample (< 2 mm). The sample was measured on a ratio of 1 part soil to 5 parts dilute salt solution of 0.01 M calcium chloride, by weight and then mixed in an end over end shaker for 1 hour and left standing for 30 minutes before a reading was taken using a standard pH probe unit. The pH method using 0.01 M $CaCo_3$ was used to standardise the pH tests of all the soil samples and was found to greatly reduce repeat sample variability. This method is also advised in Australian soil testing literature

(McKenzie *et al.* 2002, Isbell 2002). Using this method may mean that the results are from 0.5 to 1.0 pH unit lower than those obtained using distilled water (Rayment and Higginson 1992).

3.2.2.2.6 *Bulk density*

Cores of each organic horizon were taken for determining bulk density. The cores were extracted using a sharp-edged, cylindrical, steel sampler of known volume following the method in Jamison *et al.* (1950) and Creswell and Hamilton (2002). This allowed a direct measurement of soil sample mass and volume. In cases where it was not possible for the sampler to cut through roots, or to be hammered into the soil, a rectangular clod was extracted, the volume of which was determined by the water displacement method described in Creswell and Hamilton (2002). The bulk density was determined as the weight per unit volume of oven-dry soil, given as the mass of oven-dry soil divided by the total volume of the soil and expressed in kg/m^3 (Creswell and Hamilton 2002).

3.2.3 Statistical analysis of soil properties

There were originally 1193 individual soil pits and over 157 locations, but these were reduced to 1159 individual soil pits over 127 locations to meet with the minimum organic matter or organic carbon content and depth of an organosol, peat or peaty horizon, as defined by Isbell (2002) (Chapter 2).

All analyses were performed using R 2.2.1 (Gentleman and Ihaka 1997). The intrinsic soil properties chosen to classify the soil were reduced through visualisation of the variables on pairwise scatter plots, followed by Pearson's correlations (Appendix 2). On the basis of high correlation coefficients, it was decided to exclude the total soil depth and the carbon measured through wet digestion, as these were highly correlated with depth of individual horizons and organic matter, respectively. The remaining 18 variables were standardised so the values were minimum 0 and maximum 1. Kruskal's non-metric, multidimensional scaling (NMDS) was performed on the Euclidean distance matrix of the individual soil sample using the MASS package in R 2.2.1 (Venables and Ripley 2005). To ensure that the scaling did not converge to a local minimum, the NMDS was performed from 100 random starts (10,000 iterations) before a stable solution was accepted. Up to 5 dimensions were used initially, before a 3 dimensional solution was accepted based on low stress and a stressplot of stress against the distance matrix and Procrustes test (Appendix 3).

The kmeans clustering algorithm as given by MacQueen (1967) was used, using the MASS package in R 2.2.1. The algorithm works by repeatedly moving all cluster centers to the mean of their respective Voronoi sets. A hard competitive learning clustering algorithm was used, using the mclust package (Fraley and Raftery 2006) in R 2.2.1, which works by randomly drawing an observation from the matrix and moving the closest centre towards that point (Ripley 1996). A neural gas algorithm by Martinez *et al.* (1993) was used, using the mclust package in R 2.2.1, which is similar to hard competitive learning, but in addition to the closest centroid also the second closest centroid is moved in each iteration. A *c*means fuzzy clustering method was performed on the distance matrix, using the e1071 (Dimitriadou and Hornik 2006) package in R 2.2.1, which is a fuzzy version of the known *k*means clustering algorithm as well as an on-line variant, unsupervised fuzzy competitive learning (Chung and Lee 1992, Nikhil *et al.* 1996). The clusters produced from the various methods were then superimposed on the NMDS plot and visualised interactively in all dimension combinations and angles in 3-space using the GGobi and Xgobi packages (Swayne *et al.* 1998) in R 2.2.1 to select the number of clusters that matched the separations visible on the plot. To look at the ideal number of clusters in the data, v-fold cross validation was applied to a range of numbers of clusters and the resulting average distance of the observations in the cross validation from their cluster centres was assessed. Based on this analysis and plotting, the fuzzy kmeans clustering method was chosen as the model that best fitted the data. Smooth surfaces for each variable were fitted using thinplate spline fitting. The fitted values were interpolated into a regular grid using the vegan package (Oksanen 2006) in R 2.2.1. These were plotted as contours on the NMDS plot. Using a combination of the variable correlations from vector fitting and thinplate spline smoothing, strongly correlated variables could be chosen that would provide easily collected variables which could adequately describe the clusters. These variables could be selected for model building and compared with variables selected through computed model building techniques for robustness.

Stepwise model selection was performed using multinomial models for discrimination. A log-linear model via neural networks was fitted using the nnet package (Venables and Ripley 2002) in R 2.2.1. The cluster vector produced in the fuzzy kmeans clustering was used as the response and a log-linear model was fitted. Predicted class membership was calculated for random data within the given clusters. Stepwise model selection was performed based on the model AIC and a predicted class membership for the reduced model was plotted as a confusion matrix. The reduced model variables were then compared with the selected variables for their ability to predict cluster allocation. A classification decision tree was produced based on the strongest performing variables, that is, those that provide the least overlap of groups. Finally, a summary of the values of the variables of the cluster classes was produced allowing for suggested subdivisions of the soil group, organosol, to be made.

3.2.4 Soil cluster key

A soil cluster decision tree was primarily produced using the reduced set of variables found through multinomial log-linear model building and step model selection using AIC and using mvpart in the mvpart library (Ripley 2006, Oksanen 2006, De'ath 2002) R 2.2.1 which is a partitioning algorithm for multivariate data. The linear, block nature of the divisions resulted in too many variables being necessary to separate the soil cluster groups. A reduction of variables led to an overlap in clusters on the ordination plot. The broad separations found through mvpart were followed, but it was decided to construct the tree manually and to choose variables that were easily collected in the field and remote areas and inexpensive to process. The variable divisions were kept as close as possible to WRB (FAO 2006) organic soil, humification and nitrogen divisions to allow for adequate international integration.

3.3 Results

3.3.1 Ordination of soil characteristics

Correlation in a symmetric Procrustes rotation on a 2 dimensional matrix and a 3 dimensional matrix gave a 0.99 correlation, significance: < 0.001, based on 1000 permutations, this was deemed adequate to show the ordination plot in the first 2 dimensions (Appendix 3). Both vector fitting (Figure 3.3) and thinplate spline smoothing (Appendix 4) show the dominant directions in the plot for the soil variables used, with organic matter, water table, humification, drainage, bulk density and nitrogen content controlling the separation of ordination points and pH having the least influence.

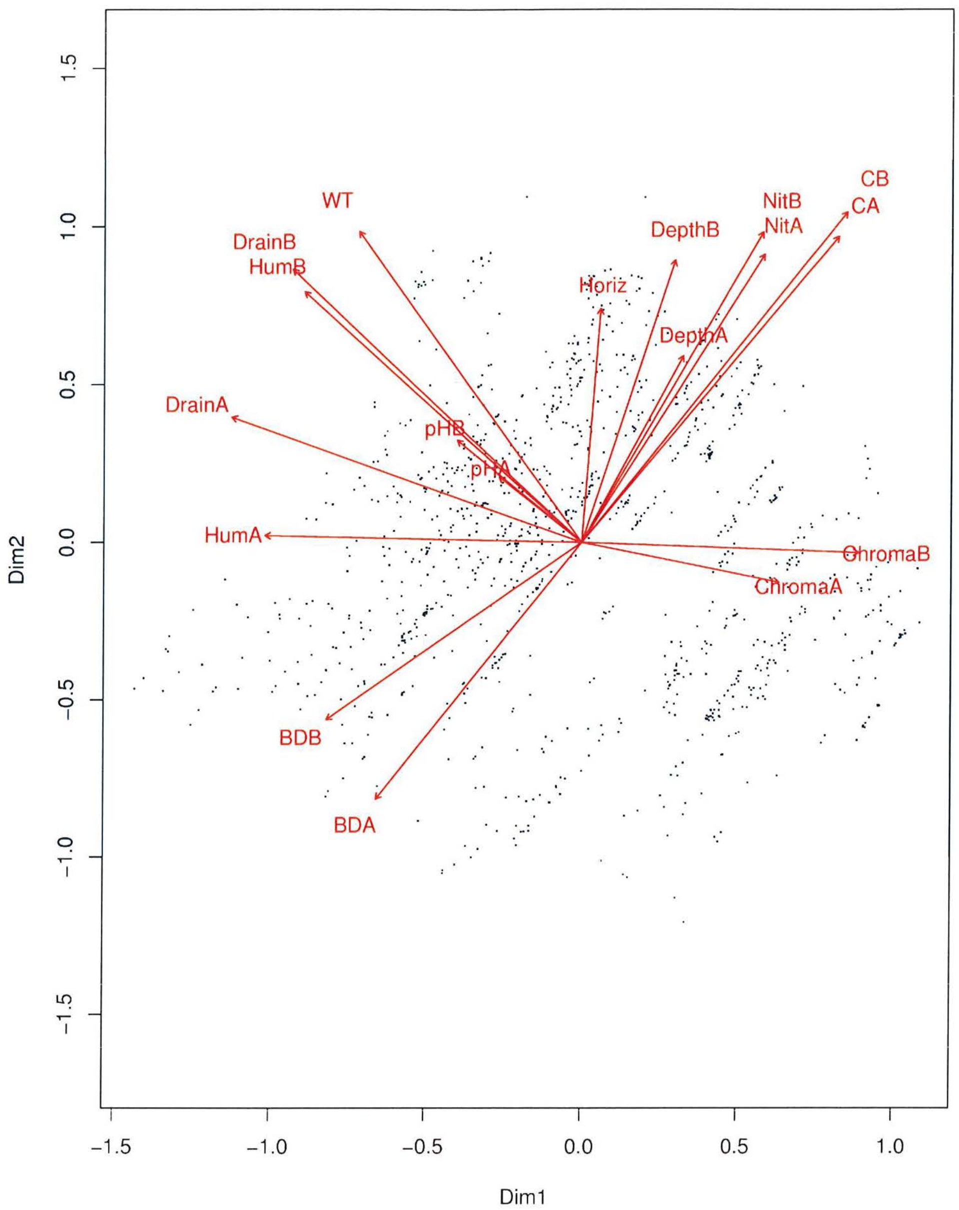

Figure 3.3

Biplot showing ordination points from first and second dimensions of the NMDS and soil variable directions within the plot. The vector abbreviations are ; BDA = bulk density in the upper horizon, BDB = bulk density in the lower horizons, CA = organic matter in upper horizon, CB = organic matter in lower horizons, ChromaA = chroma of the upper horizon, ChromaB = chroma of the lower horizons, DepthA = depth of the upper horizon, DepthB = depth of the lower horizons, DrainA = drainage in the upper horizon, DrainB = drainage in the lower horizons, Horiz = the number of horizons, HumA = humification in the upper horizon, HumB = humification in the lower horizons, NitA = total nitrogen in the upper horizon, NitB = total nitrogen in the lower horizons, pHA = pH in the upper horizon, pHB = the pH in the lower horizons, WT = water table.

In all cases the lower horizon has a stronger geometric correlation, with the strongest correlations occurring in organic matter in both the upper and lower horizons with pH, number of horizons and upper horizon chroma having the least influence (Table 3.1).

Table 3.1

The summary of results of thinplate spline smoothing and vector fitting showing the R^2, deviance explained, GCV score and significance of each variable in influencing the position on the ordination plot.

	thinplate spline R^2	*thinplate spline-% deviance explained*	*thinplate spline GCV score*	*thinplate spline - p value*	*vector R^2*	*vector p value*
Organic A (CA)	0.793	79.5	0.014	$< 2x\ 10^{-16}$	0.707	$< 2x\ 10^{-16}$
Organic B (CB)	0.808	81	0.015	$< 2x\ 10^{-16}$	0.777	$< 2x\ 10^{-16}$
Water Table	0.692	69.5	0.027	$< 2x\ 10^{-16}$	0.646	$< 2x\ 10^{-16}$
Humification A	0.566	57	0.016	$< 2x\ 10^{-16}$	0.432	$< 2x\ 10^{-16}$
Humification B	0.672	67.4	0.023	$< 2x\ 10^{-16}$	0.602	$< 2x\ 10^{-16}$
Drainage A	0.66	66.5	0.029	$< 2x\ 10^{-16}$	0.579	$< 2x\ 10^{-16}$
Drainage B	0.68	68.3	0.017	$< 2x\ 10^{-16}$	0.650	$< 2x\ 10^{-16}$
Nitrogen A	0.516	52	0.023	$< 2x\ 10^{-16}$	0.480	$< 2x\ 10^{-16}$
Nitrogen B	0.627	63	0.015	$< 2x\ 10^{-16}$	0.554	$< 2x\ 10^{-16}$
Bulk Density A	0.538	54.2	0.012	$< 2x\ 10^{-16}$	0.486	$< 2x\ 10^{-16}$
Bulk Density B	0.536	54	0.009	$< 2x\ 10^{-16}$	0.473	$< 2x\ 10^{-16}$
Chroma A	0.285	29.1	0.023	$< 2x\ 10^{-16}$	0.256	$< 2x\ 10^{-16}$
Chroma B	0.479	48.3	0.030	$< 2x\ 10^{-16}$	0.381	$< 2x\ 10^{-16}$
Horizons	0.309	31.5	0.009	$< 2x\ 10^{-16}$	0.212	$< 2x\ 10^{-16}$
Depth A	0.216	22.1	0.007	$< 2x\ 10^{-16}$	0.170	$< 2x\ 10^{-16}$
Depth B	0.463	46.7	0.011	$< 2x\ 10^{-16}$	0.368	$< 2x\ 10^{-16}$
Total Depth	0.491	49.5	0.013	$< 2x\ 10^{-16}$	0.397	$< 2x\ 10^{-16}$
pH A	0.060	6.69	0.012	$< 2x\ 10^{-16}$	0.034	$< 2x\ 10^{-16}$
pH B	0.152	15.8	0.014	$< 2x\ 10^{-16}$	0.100	$< 2x\ 10^{-16}$

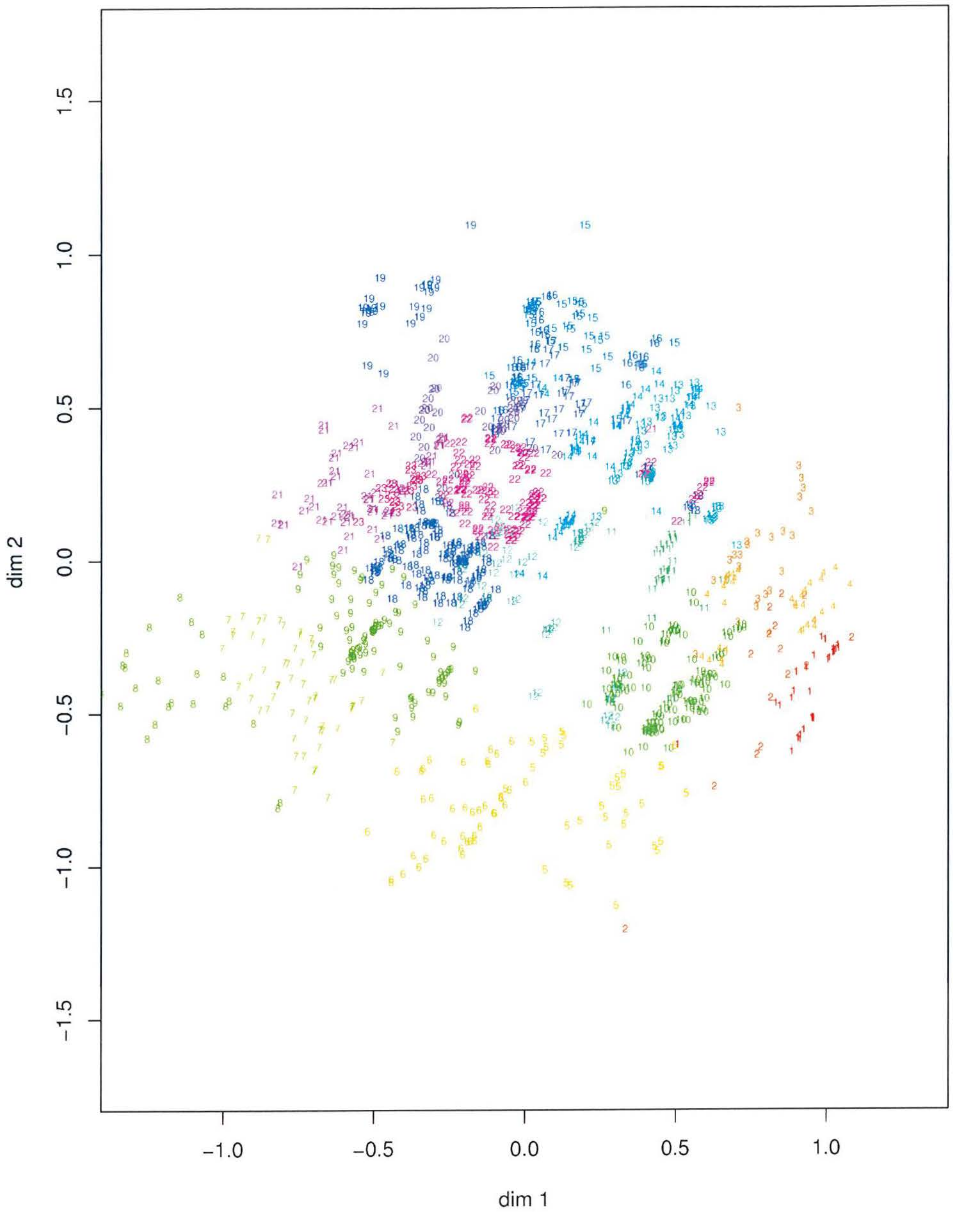

Figure 3.4

NMDS plot, stress = 10.23%, dimensions = 3, first and second dimension shown as x and y axes respectively. The 23 cluster groups assigned to individual sites and numbered accordingly on the plot.

3.3.2 Soil variables clustering

Twenty-three classes adequately described the organosol profile types (Figure 3.4). The superimposed cluster groups show adequate separation on the first 2 axes of the ordination plot, although certain cluster groups exhibit considerable overlap, even when viewed in 3 dimensional cloud space using Xgobi. This particularly applies to groups 1 and 2, groups 12 and 18 and groups 20 and 21.

3.3.2.1 Soil groups

Table 3.2 provides the soil variable averages for each cluster group and a visualisation of the soil variable summary using boxplots is provided in Appendix 5. A brief description of each cluster group is provided below.

Table 3.2

The soil variable averages for each cluster. Summary data are available in Appendix 5. The variable abbreviations are ; orgA = % organic matter in upper horizon (organic matter = organic carbon x 2 (2.3 or 2.5, depending on clay content), orgB = organic matter in lower horizons (organic matter = organic carbon x 2 (2.3 or 2.5, depending on clay content), WT = water table measured on an ordinal scale of 1-5, DrainA = drainage in the upper horizon, measured on an ordinal scale of 1-4, DrainB = drainage in the lower horizons, measured on an ordinal scale of 1-4, HumA = humification in the upper horizon, measured on an ordinal scale of 1-10, HumB = humification in the lower horizons, measured on an ordinal scale of 1-10, BDA=bulk density in the upper horizon in kg/m^3, BDB = bulk density in the lower horizons in kg/m^3, DepthA = depth of the upper horizon (cm), DepthB = depth of the lower horizons (cm), Horiz = the number of horizons, pHA = pH in the upper horizon, pHB = the pH in the lower horizons, ChromaA = chroma of the upper horizon (on ordinal scale of chroma red intensity of 0-2), ChromaB = chroma of the lower horizons (on ordinal scale of chroma red intensity of 0-2), NitA = % total nitrogen in the upper horizon, NitB = % total nitrogen in the lower horizon

Cluster	*orgA*	*orgB*	*WT*	*DepthA*	*DepthB*	*TotDepth*	*DrainA*	*DrainB*	*BDA*	*BDB*
1	89.9	76.2	0.0	17.6	44.2	61.8	1.4	2.0	0.2	0.4
2	78.8	67.6	0.0	10.4	44.7	55.1	1.3	2.0	0.3	0.4
3	89.5	87.6	0.6	28.1	67.8	96.0	1.3	3.4	0.3	0.5
4	95.0	92.4	0.1	20.1	65.7	85.8	1.0	2.0	0.3	0.4
5	60.6	31.9	0.5	8.1	26.7	34.9	2.2	2.7	0.4	0.7
6	45.8	29.1	0.8	7.6	12.5	20.1	2.5	3.0	0.5	0.7
7	44.1	19.6	2.5	9.5	27.7	37.2	3.0	4.1	0.4	0.8
8	31.0	15.1	2.5	11.9	26.1	38.0	3.8	4.4	0.6	0.8
9	64.7	27.3	2.5	11.9	34.0	46.0	2.7	4.0	0.4	0.7
10	85.5	56.2	1.0	12.2	31.2	43.3	1.9	2.6	0.3	0.6
11	95.0	89.1	1.4	14.9	41.0	55.9	1.6	2.9	0.2	0.4
12	83.2	49.0	2.4	16.7	49.8	66.5	2.0	4.1	0.3	0.6
13	96.2	92.8	0.9	25.4	85.8	111.2	1.4	3.8	0.2	0.5
14	86.0	67.3	4.9	18.7	83.7	102.4	1.6	3.7	0.1	0.3
15	95.6	93.0	3.9	22.0	150.3	172.3	2.3	4.5	0.2	0.4
16	93.7	85.9	3.3	12.4	50.6	63.0	3.3	3.7	0.2	0.3
17	94.5	91.3	3.3	15.4	94.4	109.8	2.6	4.1	0.2	0.4
18	79.4	42.1	2.8	10.1	34.9	45.0	2.8	4.4	0.3	0.7
19	92.1	77.0	4.0	21.2	82.9	104.0	3.9	5.0	0.2	0.5
20	78.2	66.2	4.6	21.5	70.8	92.3	2.8	3.9	0.2	0.5
21	85.6	67.8	3.1	10.3	39.8	50.0	3.4	4.7	0.4	0.8
22	92.6	71.2	2.8	11.4	33.7	45.1	3.0	4.3	0.2	0.6
23	80.0	43.6	3.9	19.9	30.5	50.4	3.0	4.1	0.3	0.8

Table 3.2 (continued)

Cluster	*HumA*	*HumB*	*pHA*	*pHB*	*NitA*	*NitB*	*ChromaA*	*ChromaB*	*Horiz*
1	2.0	3.3	3.3	3.3	1.1	0.8	2.6	2.0	2.0
2	2.9	3.7	4.6	4.5	1.4	1.4	1.3	1.3	2.5
3	2.7	5.8	3.5	3.4	1.4	1.2	2.0	1.8	3.2
4	2.0	4.1	3.0	3.0	1.4	0.8	1.0	1.0	3.0
5	2.6	3.8	3.6	3.6	0.6	0.3	1.8	1.5	1.8
6	3.2	4.8	3.6	3.5	0.4	0.3	1.1	0.9	2.1
7	5.1	8.5	3.6	3.8	0.5	0.2	1.2	0.6	2.4
8	6.9	8.8	3.6	3.7	0.6	0.3	0.9	0.2	2.3
9	4.0	8.4	3.5	3.6	0.6	0.3	1.4	0.8	2.3
10	2.4	4.1	3.3	3.4	1.1	0.6	2.0	1.7	2.1
11	3.6	6.5	3.4	3.4	1.2	0.6	1.4	1.4	2.0
12	2.8	7.6	3.6	3.7	1.0	0.6	1.6	1.2	2.6
13	2.9	8.6	3.5	3.3	1.3	0.9	1.8	1.0	3.1
14	1.5	4.9	3.9	3.9	1.4	1.1	1.0	1.0	2.8
15	2.5	8.8	3.4	3.8	0.9	1.0	1.6	1.0	3.4
16	3.1	7.3	3.6	3.7	1.7	1.6	1.3	1.3	2.7
17	3.2	8.8	3.3	3.4	1.3	1.1	1.4	1.0	2.8
18	3.7	8.4	3.6	3.6	0.9	0.4	1.1	1.0	2.6
19	5.5	8.6	3.7	3.8	1.7	1.5	1.0	1.0	2.3
20	4.0	6.8	4.1	4.2	1.6	1.0	1.0	1.0	2.8
21	5.3	8.9	3.7	4.0	0.7	0.4	1.1	1.0	3.0
22	3.5	8.0	3.6	3.6	1.1	0.7	1.4	1.0	2.6
23	5.5	8.9	3.4	3.7	1.2	1.0	1.0	1.0	2.1

3.3.2.2 Description of cluster groups

Cluster 1

This group is characterised by deep, reddish brown (10YR 2/2), fibrous profiles with a high organic carbon content in both the upper and lower horizons (31 – 40% organic carbon). The depth of the profile is consistently greater than 0.3 m, but typically under 1 m. Soils are well-drained with low bulk density (average 0.43 kg/m^3) due to poor humification and little compaction. No mineral horizon is present. There is no standing water table. The nature of the underlying substrate is reflected in the decrease in nitrogen and pH with depth in the profile.

Cluster 2

This group largely overlaps cluster 1 in the ordination plot, but has a slightly lower organic content (average 34% organic carbon content), higher pH (an average of pH

4.5) and higher nitrogen content (an average of 1.37%) and is, on average, shallower (0.55 m). There is no mineral horizon present.

Cluster 3

This group is characterised by highly organic, fibrous soils with over 40% organic carbon content in both the upper horizon and a lower horizons with a depth approaching 1 m. The profile has more than 2 horizons, the upper of which is well drained, with poorer drainage in the lower horizons. Nitrogen content is relatively high in the upper horizon (average 1.38%) and decreases with depth (to an average of 1.16%). These are dark reddish brown soils of 10 yr 2/2 where aerated, changing to a black chroma of 10 yr 2/1 with depth.

Cluster 4

This cluster is characterised by a very high organic carbon content of over 40% throughout the horizons. There are frequently more than 2 horizons present with a total depth of between 0.3 and 1 m. Drainage is good throughout the profile with a low bulk density and a high fibre content to depth. The soil is acidic with a relatively high nitrogen content in the upper horizon, decreasing with depth. The soil chroma is black (10 YR 2/1) throughout.

Cluster 5

This profile is characterised by a fibrous, reddish-brown (10YR 2/2) upper horizon comprising the roots of vegetation with a low bulk density grading to a lower, fibric, black horizon often mixed with sandy material from the weathered underlying regolith. The soils are well-drained and shallow with an average depth of 0.35 m and a lower horizon organic content of between 12 and 18 %.

Cluster 6

This profile is characterised by a low organic carbon content of between 12 and 18%. The total depth of this profile rarely exceeds 0.2 m. The upper horizon is black and made up of fibrous root material which grades to a more humified lower horizon which is mixed with the weathered regolith. These soils are hemic and well-drained with a very low nitrogen content.

Cluster 7

The soil profiles in this group are very low in organic carbon content (less than 12%) in both the upper and lower horizons and they therefore fall out of the organosol definition and would be classified under tenosol (Isbell, 2002). The soils are shallow at around 0.3 m deep or less and are well drained in the shallow, fibrous root horizon, grading to poor in the lower, hemic horizon. Both nitrogen content and pH are low in these black soils.

Cluster 8

This cluster is characterised by very low organic content (less than 12%) and therefore falls outside the organosol definition and would be classified under tenosol (Isbell, 2002). It is shallow with a root layer of around 10 to 15 cm on top of a sandy layer of humic material mixed with weathered regolith. The organic material is mostly moderately humified and moderately well-drained.

Cluster 9

This group is characterised by 2 distinct horizons comprising an upper, moderately high organic carbon horizon (average 33%) which is well-drained and fibrous overlying a sapric horizon with poor drainage and high bulk density and an organic carbon content of between 12 and 18%. These soils have a very low nitrogen content throughout the profile.

Cluster 10

This cluster is characterised by a high organic carbon content in the top horizon and a medium organic content (between 18 and 30%) in the lower horizons. The soil profiles are an average of 0.43 m deep and are moderately well drained and fibrous in the upper horizon sitting over a lower, darker chroma horizon which has a higher bulk density and is more humified, but still fibrous. Nitrogen is relatively high in the upper horizon, decreasing with depth.

Cluster 11

This group is characterised by very high organic carbon content, over 40%, throughout the profile. The soil is, on average, deeper than 0.5 m and has 2 horizons. The upper horizons are better drained, more fibrous and have a higher nitrogen content than the lower horizons which are more humified with a lower nitrogen content.

Cluster 12

These soil profiles are characterised by having more than 2 horizons, the lower of which can grade to clay. They are over 0.5 m deep with a permanent water table. The upper horizon is high in organic carbon which is often dark reddish brown (10 YR 2/1), fibrous, well-drained with a low bulk density and a relatively high nitrogen content sitting over waterlogged lower horizons which are black (10YR 2/1), have a high bulk density, are poorly-drained and are well-humified with a lower nitrogen content.

Cluster 13

These soil profiles are characterised by a very high organic carbon content of on average over 40% to a depth of over 1 m. There are multiple horizons with humification and bulk density increasing with depth. The upper horizon is often dark reddish brown (10YR 2/2) with a relatively high nitrogen content. The soils darken to 10YR 2/1 with depth and nitrogen content decreases.

Cluster 14

These profiles have a very high organic carbon content of over 40%, grading to around 31% with depth. The watertable is close to the surface throughout the year and is a distinctive feature in these profiles which are almost permanently waterlogged. They are characterised by a very low bulk density, reflecting the *Sphagnum* content which is often only moderately humified at depth. The pH and nitrogen content are higher than other organosols.

Cluster 15

Profiles in this group have a very high organic carbon content of over 40%, maintaining the level of organic carbon to depths of over a m. They frequently have a high water table, are poorly- drained and are, not surprisingly, found in topographic depressions. The low bulk density is largely due to the high water content and high degree of humification.

Cluster 16

This profile is characterised by a high organic carbon content of over 40% with a moderate depth of between 0.5 and 1 m. The upper horizon is hemic, moderately drained, with a low bulk density, grading to a slightly higher bulk density, sapric lower horizon. These soils have a water table that remains close to the surface (on average, within 1 m) throughout the year and have a relatively high nitrogen content which is a reflection of the underlying nutrient-rich, dolerite.

Cluster 17

This cluster is characterised by a very high organic content of over 40% to a depth of over 1 m with many profiles over 2 m. There is a shallow upper horizon of around 0.10 to 0.20 m which is well-drained and fibrous overlying lower horizons below the water table which are poorly drained, and well humified. The nitrogen content is relatively high at around 1.34%, decreasing to 1.15% with depth. The water table remains within 1 m of the surface throughout the year.

Cluster 18

These profiles have more than 2 distinct horizons with a high organic carbon content in the fibrous upper horizon and a lower organic carbon content of between 18 to 30% in the lower, more humified horizons. The average depth is around 0.45 m and nitrogen content is low, decreasing with depth.

Cluster 19

This cluster group has an organic content of between 31 to 40% to a depth of over 1 m. These are deep profiles which have a water table within 1 m of the surface throughout the year. There are usually more than 2 horizons, distinct in humification and bulk density.

Cluster 20

These profiles have a moderately high organic carbon content of between 31 and 40% to a depth of just under a metre. The water table is near the surface throughout the year with poor drainage and medium to high bulk density, increasing with depth. The soils are in distinct horizons differentiated through bulk density and humification which both increase in value with depth. Nitrogen content and pH are both higher in the upper horizons, but are still relatively high at depth which reflects the underlying nutrient-rich geology on which these profiles are found.

Cluster 21

These profiles have a moderately high organic carbon content of between 31 and 40% to a depth of around 0.5 m. They have 2 to 3 horizons distinguishable through increasing humification and bulk density with depth. Acidity increases with depth and the soils have a very low nitrogen content throughout.

Cluster 22

These profiles have a moderately high organic carbon content of between 31 and 40% to a depth of around 0.45 m. They have a water table which may be absent during the summer months or in periods without rainfall. They have poor drainage and 2 to 3 distinct horizons, distinguishable from humification. Bulk density increases with depth. Nitrogen is relatively high in the upper horizon, decreasing with depth.

Cluster 23

This cluster is characterised by soil profiles which have 2 distinct horizons; a high organic carbon content upper horizon and a lower horizon with an average organic carbon content of between 18 and 30%. The water table is high throughout the year and the soils are frequently waterlogged. Both bulk density and humification increase with depth, although there is no fibrous horizon present. The nitrogen content is comparatively high.

3.3.2.3 Soil clusters

The defining characteristics of the soil clusters relate to the dominant, linear contours of organic carbon, total nitrogen, humification, drainage, water table and bulk density. Clusters 1, 2, 3, 4, 10 and 11 are all characterised by a high organic carbon content of over 18%, a low to moderated humification, a reddish chroma, good drainage, low bulk density and no permanent water table. Clusters 5 and 6 have a low organic carbon content of < 18%, with low to moderate humification and low nitrogen content in the lower horizons. Clusters 7, 8 and 9 are also low in organic carbon content with less than 12% organic carbon, are well-humified, poorly drained and low in organic, nitrogen. Clusters 12, 13, 14, 15, 16 and 17 have a very high organic content of over 40%, are poorly-drained and well-humified. Clusters 18, 23, 21 and 22 have a moderate to high organic carbon content, are well-humified and poorly drained with a black chroma. Clusters 19 and 20 have a moderate to high organic content, are moderate to well humified, are permanently waterlogged and have a high nitrogen content

3.3.2.4 Clustering and classification key

The unsupervised clustering yielded 23 clusters which are described in terms of their defining attributes: the distinguishing variables and most commonly used variables in organic soil classification. Fuzzy clustering allowed for an overlap in cluster membership with the final decision on membership based on a chosen probability. This allows for a certain amount of flexibility in the cluster membership. The clusters described in this chapter serve as a useful basis for producing classifications or decision keys depending on the particular management purpose, but the flexibility in the probability of cluster membership can be defined by the user. As no single variable adequately describes the cluster divisions, it is necessary to describe the clusters using several of the attributes, the choice of which will depend on the user's needs. The classification key used here is produced primarily for compatibility with both national and international organic soil classification systems, but also to be useful in resolving land management issues in the organic soil producing regions in Tasmania (Figure 3.5).

It was important to use variables for the classification key that are, at the moment, commonly and globally used to define and classify organic soils for comparative purposes and, fortunately, the soil variables showing the strongest and most linear correlation with the geometric separation of the clusters and the variables produced using multinomial modelling are the variables most commonly used to define and classify organic soils, both in Australia and worldwide, notably organic carbon content, humification, waterlogging, parent material and nutrient status (Isbell 2002, Soil Survey Staff 2006, FAO 2006).

3.3.2.5 Clustering reduced soil variables

The fitting of the multinomial log-linear model followed by step model selection by

AIC, resulted in a reduced number of variables required to allocate 23 groups. The variables were; organic matter B, humification B, total depth, water table and nitrogen content B which gave a direct agreement of 23 of 23 pairs with cases in matched pairs of 86.94% using Compare Class (mclust package in R) which gave a 0.15 normalised variation of information criterion (Meila 2002).

As water table and drainage are difficult variables to measure, requiring either repeated visits and/or including continuous hydrological field measurements in inaccessible terrain, the water table variable was dropped and a few clusters were amalgamated, resulting in the following decision tree. This resulted in a total of 21 cluster groups which gave a direct agreement of 21 cluster pairs with cases in matched pairs of 85.22% using Compare Class which gave a 0.15 normalised variation of information criterion.

The final classification key (Figure 3.5) reduces 23 clusters found through unsupervised clustering techniques to 21. The initial division by organic carbon content follows the strongest contour in the ordination and allows for comparison with international definitions of organic soils and peat (Isbell 2002, Soil Survey Staff 2006, FAO 2006). The second division into humification classes follows both Australian and FAO (Isbell 2002, Soil Survey Staff 2006, FAO 2006) suborders of fibric, hemic and sapric. The third division, into percent total nitrogen, separates substrate and vegetation well in clusters providing a broad spatial dimension to the classification in Tasmania with the higher nutrient soils under rainforest vegetation and soils on Jurassic dolerite in south east, east and central Tasmania and the lower nutrient sites under quartzose Precambrian and Cambrian rocks and Quaternary sands in the west and south west of Tasmania. The final division of depth is used to distinguish uniformly deep soils found in deep depressions, such as kettle holes (cluster 15), from uniformly deep soils found in flats and valleys (cluster 17) and is a suggested family group in the Australian Soil Classification for organosols (Isbell 2002).

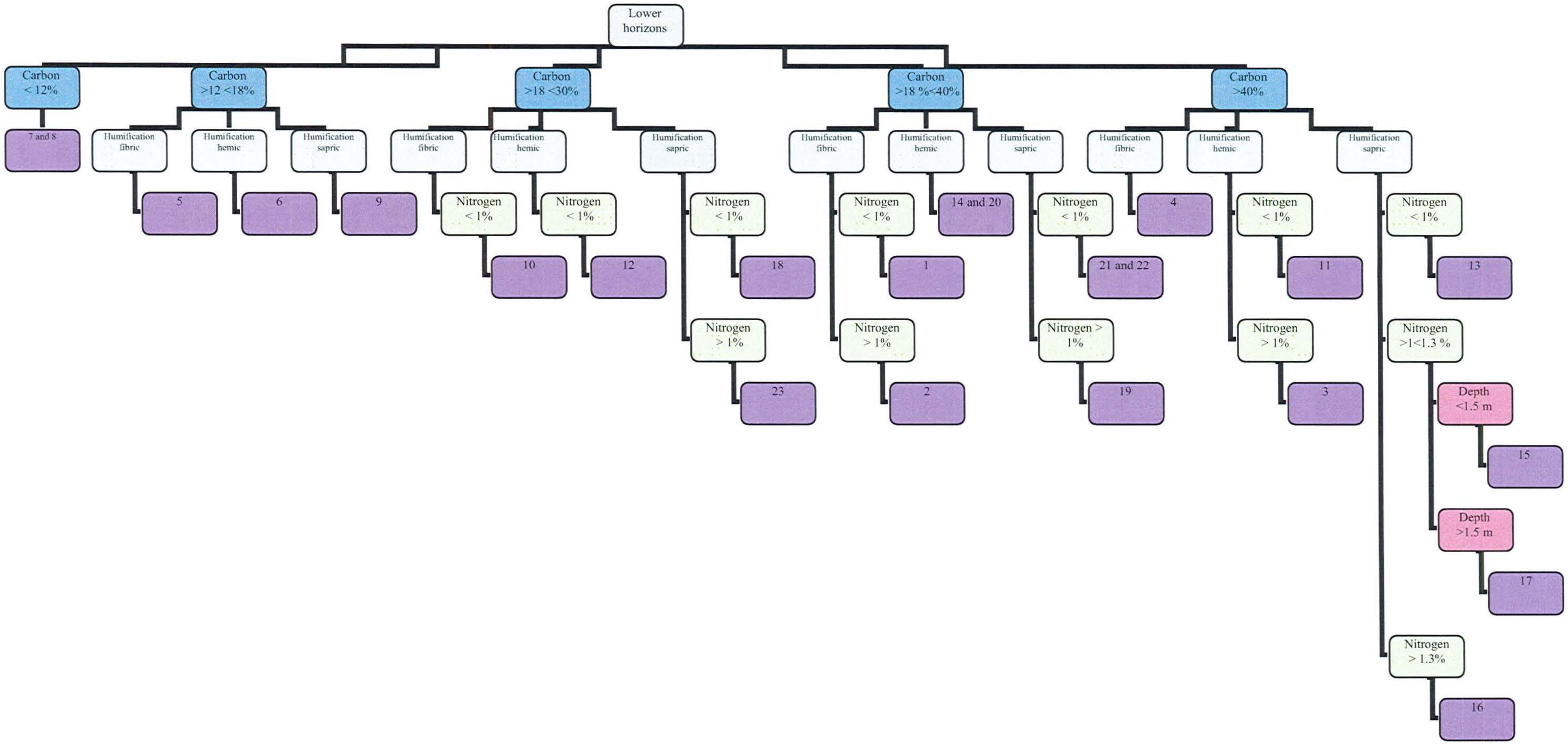

Figure 3.5

Classification key using 4 of the found through log-linear multinomial modelling to define the clusters. The tree was produced using mvpart in the mvpart library of R 2.2.1 and adjusted to use the minimum number of variables and those variables requiring the least labour-intensive collecting.

3.4 Discussion

The aim of this chapter was, through the use of unsupervised clustering techniques, to "allow the data to speak for itself", rather than provide initial cluster centres based on expected classes or groupings. It was suspected that Tasmanian organic soil processes might require descriptions not already available in the Australian Soil Classification (Isbell 2002) and that clusters produced through unsupervised clustering could then be described and used to suggesting possible suborders, great groups or subgroups for the soil order organosol, based on both soil description and soil forming processes.

3.4.1 Soil characteristics

Separation of the individual soil pits is influenced mainly by organic carbon content, total nitrogen content, humification, drainage, bulk density and water table. The dominant vector and contour in thinplate splining is organic carbon content which is also forms the first decision in the classification tree. There are only weak correlations between organic soil carbon content and the other soil variables, with low organic content found under a variety of conditions (Appendix 2). The range of organic content under diverse soil conditions may reflect the range of vegetation types and topography under which organic soils form. Total nitrogen was also variable over a wide range of soil conditions suggesting that organic soils are subject to more than one organic soil-forming process. Water table, drainage and humification of the lower horizons also characterise the organic soils. The influence of water table, drainage and humification on separation of the soil pits, can be seen in Figure 3.4, where soils with a high water table, poor drainage and well-humified organic material are grouped together. Conversely, fibric soils with no permanent water table and free drainage are grouped together. The correlations between water table, the degree of humification and drainage are significant ($p < 0.00$) and positive which suggests that the process of humification in organic soils is dominant in poorly drained soils with a high water table. Bulk density is higher in soils with a higher mineral content and in well-humified horizons. Soils with a high organic carbon content and low humification have a lower bulk density. Chroma separates the reddish, more fibric soils from the black, more humified organic soils. Interestingly high nitrogen contents occur in acid organic soils, a feature also noted in peats in the northern hemisphere (Vandecaveye 1932, Kaila 1954, Valvulo 1958, Waughman and Bellamy 1980). High nitrogen contents of around 1.37% are found in soils with a pH_{CA} of around 3.01, especially under rainforest on Precambrian quartzose rock.

3.4.2 Classification key

When considering a classification key, it was necessary to consider variables that were both defining and easily collected as much of the organic soil producing region of Tasmania is remote or inaccessible and although the water table variable correlated highly, it is a variable that requires labour-intensive monitoring. As water table, drainage, topography, burn frequency and humification were significantly correlated in the lower horizons, humification was decided as a surrogate measure and has the additional advantage of being measured on a 10 point ordinal scale. Humification requires no sample collection and no laboratory testing and can be performed in the field. Unfortunately, water table was only able to be measured on an ordinal scale in this survey and there have been no spatially and temporally extensive organosol water table studies performed in Tasmania to date. The use of water table in defining organosols in Tasmania would, however be beneficial for defining and predicting organic soil forming processes as certain clusters are distinguishable through the water table attribute in that organic matter accumulates through waterlogging (clusters 14 to 23) and some clusters (clusters 1, 2, 3, 4, 5, 6 and 13) have no water table present and organic matter accumulates under cold, highly acidic, reducing environments. Sites arranged using both drainage and topography variables can be easily distinguished, but the low number of class divisions makes the use of these variables in a key less desirable. Again, these variables would be useful in distinguishing and describing organic soils and organic soil forming processes, as there are clusters that share topographic and drainage features.

Nutrient status is not used extensively in organic soil classifications. There has been, however, extensive use of nutrient status as a distinguishing feature in peat and peatland classification (Succow 1988, Bridgham *et al.* 1996, Wheeler and Proctor 2000), as it is seen as an important indication of the underlying soil forming process. Percent total nitrogen of the lower horizons was used here to represent nutrient status for it was a clear distinguishing variable and correlated with both pH of the lower horizons, vegetation type and geology. The advantage of using nitrogen is that it is a test commonly used in conjunction with organic carbon and requires a small sample. It may also be possible, through adequate data collection, and regression, to use surrogate measures of vegetation type and underlying geology, both produced as GIS layers for the state, to provide classes of nutrient status. The acidity gradient is often used to describe organic soils and peat (Wheeler and Proctor 2000, Isbell 2002), but as all the soils were highly acidic with a pH_W of under 5.5 or pH_{CA}, of under 4.6, it was only useful as a descriptive attribute in the cluster descriptions with soils found under the highly acidic rainforest vegetation on quartzite or sand being the most acidic (cluster 4) and soils found under minerotrophic sedge-covered fens on dolerite being the least acidic (cluster 20). Percent total nitrogen produced a clearer cluster distinction with the higher nitrogen soils on dolerite and soils under rainforest experiencing infrequent burning and the lower nitrogen soils on frequently burned buttongrass moorland on Precambrian substrate, a feature also found in lowland organic soils in southwest Tasmania by Bowman *et al.* (1986). Depth has been used to distinguish clusters when necessary and is used in most definitions of organic soil in soil classifications (Avery 1980, Isbell 2002, Soil Survey Staff 2006, FAO 2006) and is easily measured in the field with a retractable probe.

The implication of the clusters and soil classification key for geoconservation are in terms of adequate recognition and reservation of the particular organic soil types. Of particular importance are the high organic carbon content, deep, fibric soils found predominantly under rainforest, which have previously not been recognised as an organosol (Isbell 2002). Mapping of organosols has been restricted to buttongrass moorland soils and *Sphagnum* peats (Isbell 2002), although organic soils under alpine, scrub and forested vegetation have been described for Tasmania (Jarman *et al.* 1982, Kirkpatrick and Dickinson 1984b, Bowman *et al.* 1986).

3.4.4 Conclusion

Tasmanian organic soils are definable in terms of their organic carbon content, degree of humification, nitrogen content and depth. Unsupervised clustering provides a clear set of organic soil clusters with particular soil characteristics which are dominated by only a few intrinsic soil properties. Understanding how these characteristics affect the management of areas with organic soils is vital.

Chapter 4

Unsupervised cluster classification - environmental factors

4.1 Introduction

The chapter aims to identify the dominant environmental variables influencing the clusters produced in chapter 3. Other soil taxonomies, reviewed in chapter 2, identify both intrinsic soil and external environmental gradients as characterising factors for organic soils. Environmental factors such as climate (Soil Classification Working Group 1998, Soil Survey Staff 2006), vegetation type (Soil Classification Working Group 1998, Survey Staff 2006) and disturbance (FAO 2006) have been used to differentiate organic soils. Additionally, peat classifications have used topography (for example, Moore and Bellamy 1974, Radforth 1977, Zoltai 1988), vegetation (for example, Cajander 1913, Eurola and Kaakinen 1979, Hulme and Blyth 1984) and hydrology (for example, Moore and Bellamy 1974, Goode and Ratcliffe 1977, Jeschke and Succow 2004) in classifying both peat and peatlands. The purpose of this chapter is to quantify the influence of certain environmental factors on organic soil characteristics, rather than include the environmental factors in the unsupervised classification.

4.2 Methods

4.2.1 Environmental characteristics

4.2.1.1 Vegetation type

Broad scale vegetation types, following Harris and Kitchener (2005), were identified where organosols were thought to occur. As it is widely recognised that the occurrence of buttongrass moorland, scrub, wet eucalypt forest and rainforest in western, lowland Tasmania are largely influenced by fire frequency (Jackson 1968), an ordinal scale was produced based on the typical length of time a vegetation type takes to recover from frequent firing (Table 4.1), according to the successional theory of Jackson (1968).

Table 4.1

Broad scale vegetation types (Harris and Kitchener 2005), with corresponding successional scale from 1-5.

Vegetation type	*Successional scale*
Highland treeless vegetation	1
Rainforest and related scrub	2
Wet eucalypt forest and woodland	3
Scrub, heathland and coastal complexes	4
Moorland, sedgeland, rushland and peatland	5

The broad scale vegetation types were used as a variable in the ordination and vector inputs, as the finer scale vegetation types (Harris and Kitchener 2005) did not yield enough replication over the full range of organosols.

An overall vegetation cover value was also estimated using the Braun-Blanquet score described in Mueller-Dombois and Ellenberg (1974). Bryophytes and dead vegetation were counted in the vegetation cover values. Before the cover values were recorded, it was established, by using the soil probe, that the particular soil features remained uniform throughout the quadrat area. The initial vegetation quadrat area was defined by methods defined by Mueller-Dombois and Ellenberg (1974) and Kent and Coker (1992), in which the size of the quadrat is determined by the species-area relationship. Despite this, the shape and size of the quadrat was often revised, especially in the alpine areas, to ensure that the underlying soil attributes remained similar.

The vegetation height is that of the average height of the tallest stratum with more than 10% cover, estimated to the nearest metre.

4.2.1.2 Topography

Slope was measured in degrees using a clinometer. The topography was assigned to a morphological type (McDonald *et al.* 1990) and those, in turn, were assigned an ordinal value representing topographic effects on run-off (Table 4.2), therefore providing an indication of soil wetness.

Table 4.2

Morphological type (McDonald *et al.* 1990), slope class McDonald *et al.* (1990) and assigned ordinal value providing a rough wetness index value.

Morphological type	*slope*	*value*
crest, hillock or ridge	32% - 56%	1
hilltop flat	< 3%	4
gently inclined lower slope	3% - 10%	4
moderately inclined upper slope	10% - 32%	1
gently inclined upper slope	3% – 10%	2
moderately inclined mid-slope	10% - 32%	2

Morphological type	*slope*	*value*
gently inclined slope	3% - 10%	3
valley flat	< 3%	5
open depression	< 3%	6
closed depression	< 3%	7

4.2.1.3 Geology

Surface geology was identified in the field from soil pits and local outcrops. Geological type was organised on a fertility scale (Table 4.3).

Table 4.3

Geology fertility descriptions and codes used in the environmental vector input.

geology	*fertility description*	*fertility value*
quartz, quartzite	nutrient-poor	1
sands	nutrient-poor	1
sandstone	nutrient-poor to moderate	2
mudstone and siltstone	nutrient-poor to moderate	2
Owen conglomerate	nutrient-poor	1
quartzose periglacial outwash	nutrient-poor	1
granite	nutrient-poor	1
dolerite	nutrient-rich	3

4.2.1.4 Altitude

Altitude was recorded for each sample as metres above sea level, taken from contour interpolation on the 1:25,000 map series (TASMAP 1984).

4.2.1.5 Burn frequency

Burn frequency, expressed as the number of fires in the last 100 years, was determined from data available from the Department of Primary Industry Water and the Environment (Marsden-Smedley pers. comm.) and also in the field using *Banksia marginata* node counts (Jarman *et al.* 1988b, Marsden-Smedley *et al.* 1999, Wills 2003) and *Leptospermum scoparium, L. nitidum* or *L. glaucescens* ring counts (Marsden-Smedley *et al.* 1999).

4.2.1.6 Climate

Latitude and longitude for each site was measured using a hand held GPS unit and the data entered into BIOCLIM (McMahon 1985, Busby 1986, Nix and Busby 1986). The climate variables used were: total annual precipitation, total precipitation during the driest quarter, total precipitation during the wettest quarter of the year, total annual number of rain days, total number of rain days for the driest quarter of the year, total number of rain days for the wettest quarter of the year, total annual evaporation, total evaporation for the driest quarter of the year, total evaporation for the wettest quarter of the year, average annual minimum temperature, average annual maximum temperature, minimum temperature of the driest quarter of the year, minimum temperature of the wettest quarter of the year, maximum temperature of the driest quarter of the year, maximum temperature of the wettest quarter of the year, average annual radiation, average radiation for the driest quarter of the year and average radiation for the wettest quarter of the year.

4.2.2 Statistical analysis of environmental properties

A pairwise scatterplot and correlation co-efficients were produced to analyse the relationships between the environmental variables. The environmental variables were then fitted to the NMDS plot, with 1,000 permutations using the vegan package in R 2.2.1, to visually examine the relationships with the soil groupings and attributes. To examine possible non-linear environmental relationships with soil groupings, the addition of thinplate smoothing splines to create contour plots as an overlay to the NMDS plot for each environmental variable was performed using the vegan package in R 2.2.1. A Mantel test was performed on the soil variable matrix and the environmental variable matrix. The variables identified as significant in correlating with the ordination were used to perform another group of clusters based on the environmental correlates which was then compared with the cluster group from the soil attributes using the package mclust in R 2.2.1. This, along with variable boxplots, aided in describing the environmental correlates of the soil groups. Summary tables were produced for soil characteristics, controlled for successional vegetation stages, topography, climate, altitude and geology.

Climate variables were ordinated separately using non-metric multi-dimensional scaling in the vegan package in R 2.2.1. Hierarchical and kmeans clustering was performed on the distance matrix and 5 distinct climatic groups were found. Summary tables and boxplots were produced for each climatic cluster in terms of the environmental and climate variables and a mosaicplot produced to compare soil cluster and climate cluster membership. A multinomial log-linear model was run on all the environmental variables for the cluster grouping and through stepwise selection using AIC.

4.3 Results

4.3.1 Environmental variables

Pairwise scatterplots of the environmental variables showed correlations between many of the climate variables (Appendix 7). Further vector fitting and thinplate spline smoothing added to the ordination plots shows that all of the environmental variables were significant (Table 4.4, Appendix 8). This is consistent with the correlation of the distance matrices of the soil variables and environmental variables yielding a Mantel statistic of 0.27 with a significance of < 0.001. The variables that showed best correlation with the ordination geometry were vegetation type, vegetation height, geology, topography, altitude, burn frequency, precipitation in the driest quarter of the year, the temperature variables and the radiation variables (Figure 4.1, Table 4.4, Appendix 8). When a reduced group of variables (vegetation type, vegetation height, geology, topography, altitude, burn frequency, precipitation in the driest quarter of the year, the temperature variables and the radiation variables) were chosen for their high correlation scores and linearity, as shown in the thinplate spline smoothing results, the Mantel test on the new distance matrices yielded a score of 0.35 and a significance of < 0.001.

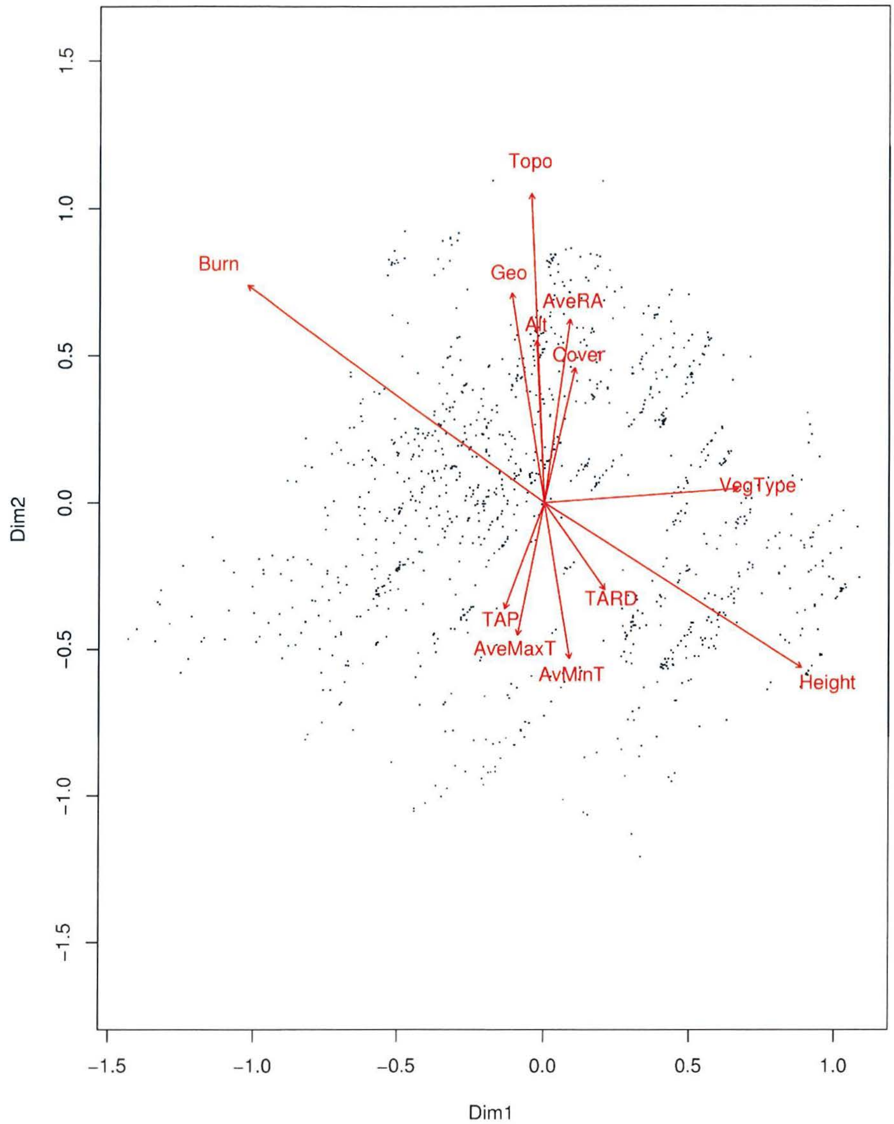

Figure 4.1

Biplot showing NMDS plot and environmental vectors in the first 2 dimensions. The abbreviations are as follows; AveMaxT = average annual maximum temperature, AveMinT = average annual minimum temperature, AveRA = average annual radiation, Burn = burn frequency, Cover = vegetation cover, Alt = altitude in metres above sea level, Geo = geology, Height = vegetation height, TAP = total annual precipitation, TARD = total annual rain days, Topo = topography, VegType= vegetation type.

Table 4.4

The summary of results of thinplate spline smoothing and vector fitting showing the R^2, deviance explained, GCV score and significance of each environmental variable correlating with the geometry of the sample positions on the ordination plot. Abbreviations used in the table are explained in Appendix 6.

	thinplate spline smoothing (adj.) R^2	*thinplate spline deviance explained*	*thinplate spline GCV score*	*thinplate spline p value*	*vector R^2*	*vector p value*
Vegetation height	0.545	54.9	0.022	$< 2 \times 10^{-16}$	0.410	$< 1 \times 10^{-4}$
Burn frequency	0.527	53.1	0.048	$< 2 \times 10^{-16}$	0.468	$< 1 \times 10^{-4}$
Vegetation type	0.358	36.3	0.104	$< 2 \times 10^{-16}$	0.239	$< 1 \times 10^{-4}$
Topography	0.306	31.2	0.057	$< 2 \times 10^{-16}$	0.244	$< 1 \times 10^{-4}$
AveRadDQ	0.258	26.4	0.386	$< 2 \times 10^{-16}$	0.119	$< 1 \times 10^{-4}$
AveRA	0.245	25.2	0.037	$< 2 \times 10^{-16}$	0.120	$< 1 \times 10^{-4}$
Geology	0.231	23.7	0.127	$< 2 \times 10^{-16}$	0.161	$< 1 \times 10^{-4}$
AveMinT	0.224	23	0.070	$< 2 \times 10^{-16}$	0.214	$< 1 \times 10^{-4}$
MinTWQ	0.224	22.9	0.071	$< 2 \times 10^{-16}$	0.214	$< 1 \times 10^{-4}$
MinTDQ	0.222	22.7	0.070	$< 2 \times 10^{-16}$	0.211	$< 1 \times 10^{-4}$
MaxTWQ	0.219	22.4	0.055	$< 2 \times 10^{-16}$	0.205	$< 1 \times 10^{-4}$
Altitude	0.216	22.1	0.064	$< 2 \times 10^{-16}$	0.203	$< 1 \times 10^{-4}$
DQ	0.211	21.7	0.042	$< 2 \times 10^{-16}$	0.047	$< 1 \times 10^{-4}$
AveMaxT	0.203	20.9	0.046	$< 2 \times 10^{-16}$	0.185	$< 1 \times 10^{-4}$
AveRadWQ	0.194	20.1	0.03	$< 2 \times 10^{-16}$	0.102	$< 1 \times 10^{-4}$
TEWQ	0.192	19.7	0.066	$< 2 \times 10^{-16}$	0.181	$< 1 \times 10^{-4}$
TAP	0.189	19.6	0.044	$< 2 \times 10^{-16}$	0.032	$< 1 \times 10^{-4}$
MaxTDQ	0.188	19.4	0.034	$< 2 \times 10^{-16}$	0.147	$< 1 \times 10^{-4}$
WQ	0.170	17.7	0.043	$< 2 \times 10^{-16}$	0.024	$< 1 \times 10^{-4}$
TE	0.159	16.5	0.048	$< 2 \times 10^{-16}$	0.143	$< 1 \times 10^{-4}$
TEDQ	0.131	13.8	0.040	$< 2 \times 10^{-16}$	0.108	$< 1 \times 10^{-4}$
Vegetation cover	0.113	12	0.009	$< 2 \times 10^{-16}$	0.070	$< 1 \times 10^{-4}$

	thinplate spline smoothing (adj.) R^2	*thinplate spline deviance explained*	*thinplate spline GCV score*	*thinplate spline p value*	*vector R^2*	*vector p value*
TRDDQ	0.092	9.94	0.027	$< 2 \times 10^{-16}$	0.045	$< 1 \times 10^{-4}$
TARD	0.050	5.71	0.027	$< 2 \times 10^{-16}$	0.007	0.0244
TRDWQ	0.043	5.02	0.026	$< 2 \times 10^{-16}$	0.007	0.0330

4.3.2 Environmental variables in the cluster groups

Environmental variable averages for each cluster group are shown in Table 4.5 with boxplots for each variable available in Appendix 5. The number of environmental variables that explained the cluster groupings was reduced to 15: vegetation type, vegetation height, topography, geology, altitude, burn frequency, total precipitation in the dry quarter, total evaporation in the dry quarter, total evaporation in the wet quarter, average minimum temperature, minimum temperature in the dry quarter, average maximum temperature, maximum temperature in the dry quarter, average radiation in the dry quarter and average radiation in the wet quarter. This reduced set of environmental variables also showed best distinction between cluster groups in the boxplots in Appendix 5. Seventy percent of the individuals in the 23 soil groups were matched using the reduced set of variables. The 30% mis-match was mostly in groups that overlapped on the ordination plot. The table can be seen in Appendix 7.

Table 4.5

The environmental variable averages for each cluster. The variable codes are explained in full in the methods section of this chapter. Box plots of the environmental variables for each cluster are in Appendix 5.

cluster	*VegType*	*Topo*	*Cover*	*Height*	*Geo*	*Alt*	*Burn*	*TAP*	*DQ*	*WQ*	*TARD*
1	2.3	3.3	93.5	21.1	1.0	39	0.7	2161	386	661	240.4
2	2.3	2.7	97.0	15.5	1.3	662	1.0	2197	369	691	239.8
3	3.3	3.2	98.0	11.5	1.2	343	1.6	2298	413	697	245.7
4	2.0	2.9	93.1	18.4	1.0	517	0.5	2308	396	717	247.2
5	3.5	3.7	95.2	17.0	1.1	63	1.3	1859	347	558	233.4
6	4.6	1.9	86.3	0.7	1.0	295	2.8	2244	398	695	246.0
7	4.5	4.5	90.9	3.4	1.3	374	2.5	2099	367	639	235.4
8	4.2	4.3	93.6	0.5	1.8	528	2.9	2223	390	669	240.6
9	4.6	4.2	93.1	2.4	1.3	406	2.7	2067	365	625	237.0
10	2.9	3.1	92.7	20.4	1.3	170	1.1	1767	324	533	237.6
11	3.4	1.8	95.4	10.5	1.4	566	1.0	2419	431	732	249.6
12	4.6	4.2	98.3	3.3	1.6	374	2.6	1693	307	504	225.1
13	3.5	3.1	99.2	2.7	1.0	295	1.9	2225	390	682	245.6
14	1.0	6.4	100.0	0.2	3.0	1233	3.0	1515	241	485	236.6
15	2.1	6.1	98.0	0.6	2.5	792	3.0	1608	268	505	233.2
16	2.4	4.6	100.0	7.2	2.3	826	2.7	1509	258	465	231.6
17	4.3	4.6	98.6	3.0	1.2	250	2.8	1706	302	527	235.7
18	4.7	4.9	99.9	3.5	1.2	402	2.6	2132	380	644	240.6
19	2.9	6.0	100.0	0.3	2.0	604	3.0	1800	312	560	237.8
20	1.0	5.8	100.0	0.4	2.8	1203	2.8	1471	245	457	232.9
21	4.7	5.2	99.7	0.4	1.6	522	3.0	2412	416	731	235.3
22	4.7	4.2	100.0	1.0	1.2	611	2.8	2465	444	739	242.9
23	5.0	2.4	100.0	0.9	1.2	526	3.0	2758	501	828	243.3

Table 4.5 (continued)

cluster	*TRDDQ*	*TRDWQ*	*TE*	*TEDQ*	*TEWQ*	*AvMinT*	*MinTDQ*	*MinTWQ*	*AvMaxT*
1	46.5	68.1	841	328	117	6.8	9.3	4.4	15.2
2	45.1	69.2	774	309	100	3.7	6.4	1.3	11.8
3	47.3	69.9	796	315	106	5.6	8.0	3.3	13.4
4	47.1	70.6	770	308	100	4.1	6.8	1.8	12.6
5	45.1	66.2	837	324	117	6.7	9.3	4.4	14.8
6	47.2	70.0	823	325	111	5.6	8.2	3.3	13.9
7	45.1	66.6	787	312	105	4.9	7.6	2.4	13.6
8	45.7	68.7	769	307	100	4.1	6.7	1.7	12.8
9	45.5	66.9	788	312	105	5.0	7.7	2.6	13.5
10	46.2	67.2	801	313	111	6.3	8.8	4.0	13.9
11	47.8	71.1	751	299	98	4.3	6.8	2.0	12.0
12	43.4	63.1	782	309	104	5.0	7.6	2.6	13.3
13	47.2	69.7	795	314	107	5.3	7.9	3.0	13.8
14	43.6	69.2	673	280	78	1.0	3.7	-1.2	8.7
15	43.7	67.2	738	300	92	3.0	5.6	0.6	11.0
16	43.3	66.9	727	294	92	2.9	5.6	0.6	10.7
17	45.3	67.0	812	319	110	5.9	8.5	3.6	14.0
18	46.2	68.0	777	308	103	4.8	7.4	2.4	13.2
19	45.1	68.3	759	304	98	4.1	6.7	1.8	11.9
20	43.2	67.4	666	277	77	1.2	3.9	-1.1	8.7
21	44.4	67.4	800	318	104	3.9	6.7	1.4	13.2
22	46.2	69.3	769	308	98	3.7	6.4	1.3	12.3
23	46.2	69.7	798	318	104	4.2	6.9	1.8	12.9

Table 4.5 (continued)

cluster	*Trange*	*MaxTDQ*	*MaxTDQ*	*MaxTWQ*	*AveRA*	*AvRadDQ*	*AvRadWQ*
1	8.4	18.9	18.9	12.1	10.7	15.5	6.1
2	8.1	16.5	16.5	7.7	11.1	16.1	6.5
3	7.9	17.5	17.5	9.8	11.0	15.8	6.5
4	8.5	17.3	17.3	8.6	10.8	15.7	6.3
5	8.1	18.4	18.4	11.8	11.0	16.0	6.4
6	8.3	18.2	18.2	10.3	10.9	15.8	6.4
7	8.7	18.0	18.0	9.8	10.9	15.8	6.4
8	8.7	17.4	17.4	8.7	11.1	15.9	6.5
9	8.5	17.8	17.8	9.8	10.9	15.9	6.3
10	7.6	17.5	17.5	10.9	11.0	16.1	6.5
11	7.7	16.4	16.4	8.2	10.8	15.5	6.4
12	8.3	17.4	17.4	9.7	11.3	16.4	6.7
13	8.4	18.0	18.0	10.2	10.7	15.6	6.2
14	7.7	14.1	14.1	3.7	12.1	17.8	7.1
15	8.1	15.9	15.9	6.7	11.8	17.3	6.9
16	7.8	15.4	15.4	6.4	11.9	17.4	7.0
17	8.1	17.9	17.9	10.6	11.4	16.6	6.7
18	8.4	17.6	17.6	9.5	21.0	18.5	7.5
19	7.8	16.4	16.4	8.0	11.4	16.6	6.6
20	7.5	14.0	14.0	3.8	12.1	17.7	7.2
21	9.3	18.1	18.1	8.9	10.9	15.7	6.3
22	8.6	17.2	17.2	8.0	10.9	15.6	6.5
23	8.7	17.8	17.8	8.8	10.6	15.1	6.3

4.3.3 Environmental factor interactions

The influence of environmental factors on soil characteristics is particularly noticeable when controlled for climate, altitude, topography, vegetation type and/or geology.

4.3.3.1 Lowland vegetation succession

The organic soil characteristics are different across successional stages from buttongrass through scrub, wet eucalypt forest to rainforest, when topography and geology are controlled (Table 4.6). Soil samples taken at five locations in the west of Tasmania from each vegetation stage on siliceous Owen Conglomerate across a fire and successional boundary showed that the depth of soil, organic carbon content and total nitrogen content increased from moorland through to rainforest as plant remains accumulated. Soils also became more fibric and acidic as successional stages progressed. There was also a decrease in humification and a decrease in bulk density from buttongrass to rainforest. The drainage of the soil improved with well drained soils under the rainforests. Organic soils were noted to progress from organic soils on clays to mineral soils in lowland vegetation succession on dolerite.

Table 4.6

The data were collected from Mount Murchison and the Tyndall Range in the west of the state on Owen Conglomerate on slopes of between 15° and 30°. The variables are explained in full in Chapter 3 Methods. The values provided are the mean, with the minimum and maximum values given in brackets.

variables.	*moorland*	*scrub*	*rainforest*
water table	1 (1-1)	0 (0-0)	0 (0-0)
number of horizons	2 (2-2)	3 (2-3)	4 (3-4)
organic soil depth (m)	0.2 (0.1-0.3)	0.7 (0.5-0.9)	1.5 (0.75–190)
organic carbon content of soil below surface litter layer to 0.1m (%)	0.2 (0.15-0.21)	0.45 (0.41-0.48)	48.5 (48.3-49.4)
organic carbon content of further horizons combined(%)	15 (12-16)	41 (35-48)	49 (48.5-49.3)
total nitrogen content of soil below surface litter layer (%)	0.25 (0.21-0.27)	0.82 (0.77-1.02)	1.27 (1.15-1.34)
total nitrogen of subsequent horizons combined (%)	0.14 (0.11-0.19)	0.41 (0.33-0.78)	0.82 (0.62-0.99)
humification of soil below surface litter layer to 0.1m	4	3	2
humification of subsequent horizons combined	6	5	5
pH of soil below surface litter layer to 0.1m	3.6 (3.6-3.7)	3.2 (3.2-3.3)	2.7 (2.6-2.9)

variables.	*moorland*	*scrub*	*rainforest*
pH of subsequent horizons combined	3.6 (3.6-3.7)	3.2 (3.1-3.3)	2.9 (2.9-3)
drainage of soil below surface litter layer to 0.1m	3	1	1
drainage of subsequent horizons combined	3	3	2
bulk density (kg/m^3) of soil below surface litter layer to 0.1m	0.5 (0.4-0.6)	0.3 (0.2-0.4)	0.3 (0.2-0.3)
bulk density (kg/m^3) of subsequent horizons combined	0.6 (0.4-0.7)	0.6 (5-0.8)	0.4 (0.3-0.4)
vegetation height (m)	0.5 (0.3-0.6)	2.5 (1.5-3)	14 (12-15)

4.3.3.2 Burn frequency and topography in upland areas

In order to fully understand the influence of fire frequency on the development and characteristics of soils in upland areas, it is necessary to control for topography, geology and altitude. The results in Table 4.7 show that, in the Tyndall Range, on Precambrian quartzite, higher fire frequency on slopes and well-drained areas has a negative effect on organic carbon, nitrogen and depth. No difference is discernible in waterlogged areas. Unfortunately, not enough data were collected from within each climatic region to analyse nutrient-poor upland areas with different burn frequencies, although soil profiles taken on the eastern Central Plateau seem to exhibit a similar pattern. On the Central Plateau the minerotrophic, waterlogged sites show little difference between burned and non-burned areas, with low soil organic carbon due to the volume of water in the profiles and high nitrogen content due to the minerotrophic water. Better-drained sites in the eastern Central Plateau experiencing infrequent fires have an organic rich and fibrous upper horizon, often over a mineral soil. Where fires are frequent, the soils are shallow with a humose horizon, have a lower organic content and a lower nitrogen content.

Table 4.7

Upland areas of Tasmania controlled for geology (Precambrian quartzite), regionality (Tyndall Range) and altitude (> 900 m a.s.l.) correlations and significance for burn frequency (Chapter 4 Methods) and topography (Chapter 4 Methods).

correlation with burn frequency	*slopes and well drained areas with no water table present* *topography class 1*	*flats, valleys and depressions with water table near surface for most of the year* *topography class 5*
organic carbon upper horizon	-0.33 ($p = 0.01$)	-0.04 ($p = 0.4$)
organic carbon lower horizons	-0.33 ($p = 0.01$)	-0.06 ($p = 0.22$)
soil organic carbon density upper horizon	-0.50 ($p < 0.000$)	0.07 ($p = 0.39$)
soil organic carbon density lower horizon	-0.33 ($p = 0.01$	0.05 ($p = 0.48$)
nitrogen upper horizon	-0.42 ($p = 0.002$)	0.04 ($p = 0.64$)
nitrogen lower horizon	-0.39 ($p = 0.004$)	-0.12 ($p = 0.14$)
total depth	0.51 ($p < 0.000$)	0.07 ($p = 0.24$)
vegetation type	0.77 ($p < 0.000$)	0.07 ($p = 0.41$)

4.3.3.3 Burn frequency and topography in lowland areas

In lowland areas, on nutrient-poor geology, burn frequency shows a higher correlation on slopes than in depressions and flats (Table 4.8), with organic carbon content, organic carbon density, nitrogen content, soil depth and vegetation type showing a significant correlation with burn frequency on well-drained slopes. On depressions and flats with a high water table, the influence of burn frequency is not as strong, with lower correlations between fire frequency and organic carbon content in the upper horizon, nitrogen content in the upper horizon, organic carbon density in the lower horizon and vegetation. No significant correlation between fire frequency and organic carbon in the lower horizon, organic carbon density in the upper horizon, total nitrogen in the lower horizon and total depth was found.

Table 4.8

Correlation with burn frequency for the following variables with topography, altitude (below 300 m) and geology (nutrient-poor) controlled.

correlation with burn frequency	*slopes and well drained areas with no water table present topography class 1*	*flats and valleys with water table near surface for most of the year topography class 5*
organic carbon upper horizon	-0.59 ($p < 0.000$)	-0.27 ($p < 0.000$)
organic carbon lower horizons	-0.76 ($p < 0.000$)	0.004 ($p = 0.96$)
soil organic carbon density upper horizon	-0.16 ($p < 0.000$)	0.12 ($p = 0.09$)
soil organic carbon density lower horizon	-0.53 ($p < 0.000$)	0.13 ($p = 0.04$)
nitrogen upper horizon	-0.78 ($p < 0.000$)	-0.40 ($p < 0.000$)
nitrogen lower horizon	-0.68 ($p < 0.000$)	0.09 ($p = 0.19$)
total depth	-0.54 ($p < 0.000$)	0.003 ($p = 0.97$)
vegetation type	0.88 ($p < 0.000$)	0.59 ($p < 0.000$)

4.3.3.4 Climate variables

As many of the climate variables are correlated (Appendix 7), the broad trends are summarised as follows.

Sites in the eastern edge of the Central Plateau, Mount Field, Hartz Mountains, The South West Coast and Snug Tiers (cluster groups 10, 12, 14, 15, 16, 17, 19 and 20) experience the least amount of rainfall throughout the year with sites on the eastern edge of the Central Plateau experiencing the least number of rain days annually (cluster groups 14 and 15) and in the driest quarter of the year (clusters 14, 15, 16 and 20). Evaporation is higher in coastal, low-lying areas (cluster groups 1 and 5) and lowest in mountain areas (cluster groups 14 and 20). Radiation is higher in mountain areas (especially cluster groups 14, 15, 16 and 20) and lowest in low-lying, coastal sites (especially cluster groups 1, 2, 4, 13, 18 and 23). The highest average annual maximum and average maximum temperatures during the driest quarter of the year are also found on low-lying coastal sites (cluster groups 1, 5, 6, 7, 9, 10 and 20) and the lowest temperatures in mountain regions (cluster groups 14, 15, 16 and 20) . Where total annual precipitation, total precipitation over the driest quarter of the year and total annual number of rain days are lower, lower temperatures are evident, with organic soil development in the eastern part of the state only occurring on high mountain plateaux

4.3.3.5 Climatic regions through clustering

There were five distinct organosol-producing climatic regions (Figure 4.2).

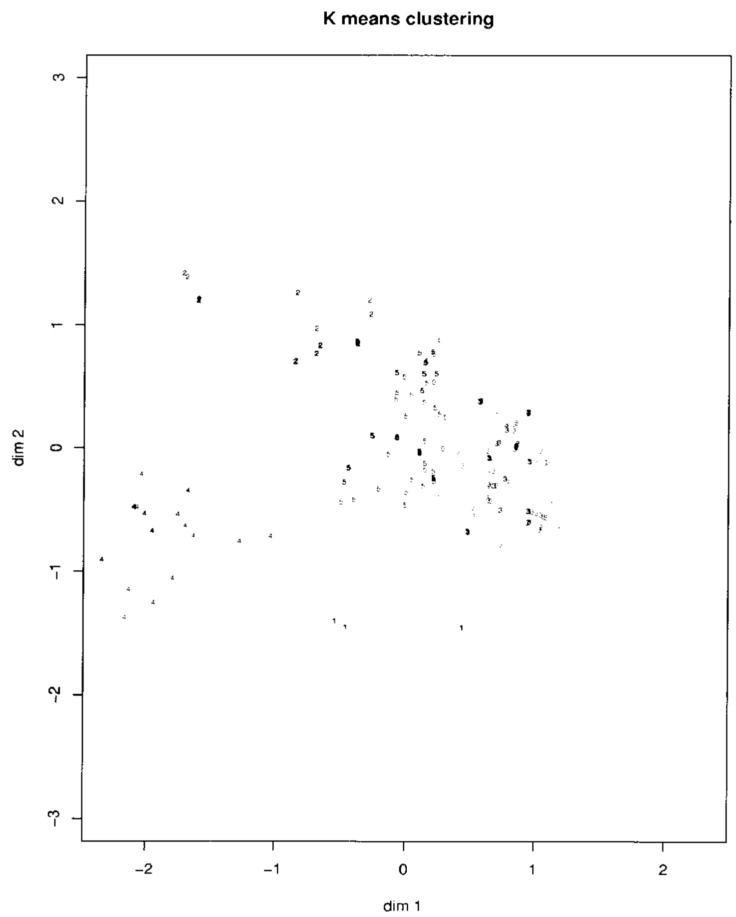

Figure 4.2

Non-metric multidimensional scaling plot of the first 2 of 3 dimensions. Stress = 4.57%. The sites are coded according to the 5 climatic cluster groups from 1 to 5 produced through kmeans clustering.

The climatic variables corresponded to geographic climatic regions in Tasmania, a summary of the 5 regions' climatic and environmental attributes can be viewed in Appendix 10 and Appendix 11, and a set of corresponding boxplots are provided in Appendix 9. There is a clear division between clusters 2 and 4 which are both high altitude at over 650 m above sea level and clusters 1, 3 and 5 which are all below 750 m above sea level. There is a further separation between high rainfall western areas and lower rainfall eastern and central highland areas with clusters 2 and 5 in the west and south-west inland regions of Tasmania with a rainfall over 1600 mm per annum and the central and eastern regions with clusters 1 and 4 with an annual rainfall under 1700 mm. Cluster 3 is coastal west and south west with lower annual rainfall and higher temperatures.

When the 5 climatic groups were compared with the 23 soil cluster groups, a match of 57 % was found. Details can be viewed in Figure 4.3 which shows that certain soil clusters, such as soil clusters 1, 14, 16 and 20, are found in one climatic group, while some soil clusters, such as soil cluster groups 7, 8, 9, 10, 12, 13 and 18, occur in several climatic regions.

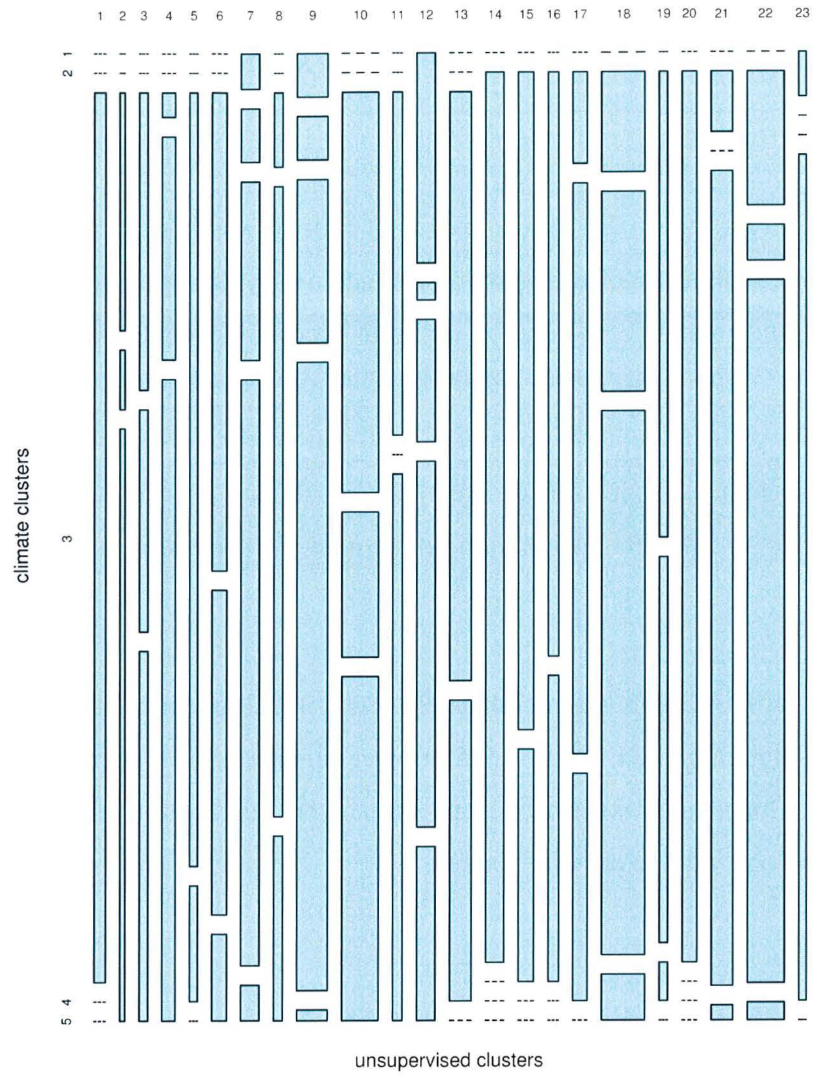

Figure 4.3

Mosaicplot showing climatic group membership of each soil cluster group. The areas of the rectangular regions are proportional to the number of observations in each group.

4.3.4 *Descriptions of environmental characteristics for unsupervised soil cluster groups*

Cluster 1

All of the soil profiles in this cluster are found under low altitude (under 300 m a.s.l.) long unburned rainforest or coastal rainforest and overlying a low nutrient geology or Holocene sands (sands considered a substrate according to McDonald *et al.* 1990, Isbell 2002). The nature of the underlying substrate is reflected in the decrease in nitrogen and pH with depth in the profile. All soil profiles in this cluster are on low to medium gradient slopes. They are found in climate cluster 3 in areas of high rainfall (1,580 to 2,449 mm per annum) in the west and south west of Tasmania.

Cluster 2

These soil profiles are found in climate clusters 2 and 3, under rainforest vegetation, in areas of high rainfall (1,409 to 2,535 mm per annum) in the west and south west of Tasmania which have experienced one burn event in the last 100 years on low nutrient geology with no mineral horizon.

Cluster 3

These soils are found in climate clusters 2 and 3 on nutrient-poor geology under rainforest recovering from fire, rainforest scrub, coastal forest of *Leptospermum* species or *Melaleuca* species on Holocene sands in the west and southwest of Tasmania.

Cluster 4

These soils are found in climate clusters 2 and 5, under rainforest vegetation, and related scrub which has been subjected to recent fires, on nutrient-poor geology in west and south-west Tasmania.

Cluster 5

This profile is found in climate cluster 3, under mixed forest or scrub with an average of 1 to 2 burns in the last 100 years.

Cluster 6

All of the soil profiles found in this group occur in climate clusters 3 and 5, over nutrient-poor geology on slopes with buttongrass moorland that has experienced repeated burning over the last 100 years.

Cluster 7

These soils are mostly found in climate clusters 3 and 5, on nutrient-poor geology under frequently burned buttongrass moorlands in topographic depressions.

Cluster 8

This cluster occurs on nutrient-poor geology on frequently burned buttongrass moorland on moderate to steep slopes. This profile group occurs in climate groups 2, 3, 4 and 5.

Cluster 9

These soils are mostly found under buttongrass moorland in valleys or flats. This profile group occurs through all the climate clusters, but predominantly in clusters 3 and 5.

Cluster 10

These soils most commonly occur in climate clusters 3 and 5, under wet scrub to mixed forest which have experienced, on average, 2 to 3 burns over the last 100 years on nutrient-poor geology or Holocene sand.

Cluster 11

These are soils which have experienced one burn in the last 100 years on low nutrient geology on hill top saddles under alpine scrub or sub-alpine buttongrass moorland in climate clusters 2 and 3.

Cluster 12

These sites are often found in climate clusters 1, 3 and 5, in valleys or depressions with buttongrass moorland vegetation on nutrient-moderate geology with 2 to 3 burns in the last 100 years.

Cluster 13

These profiles are found on nutrient-poor geology on mounds or saddles which are well-drained, and also in coastal flats on Holocene sands. They occur in climate clusters 2, 3 and 5.

Cluster 14

These profiles are characterised by the underlying nutrient-rich geology on which they are found. The profiles in this group are found in climate cluster 4, in topographic depressions and valleys in the Walls of Jerusalem and Central Plateau on dolerite and the vegetation is usually dominated by sedges or *Sphagnum*.

Cluster 15

Profiles in this group are found on nutrient-rich geology in topographic depressions in climate clusters 3 and 4. They are dominated by sedges in coastal areas and *Sphagnum* in alpine areas.

Cluster 16

The profiles are found in climate cluster 4, in valleys in the Central Plateau and The Walls of Jerusalem in minerotrophic water regimes on dolerite.

Cluster 17

These profiles are found in climate clusters 3 and 5 on medium-nutrient geology or on Holocene sands in valleys or depressions under restiad or buttongrass moorlands which are frequently burned.

Cluster 18

These profiles are found on nutrient-poor geology in climate clusters 3, 4 and 5, with an average of 2 to 3 burns in the last 100 years. The dominant vegetation type is buttongrass moorland on flats.

Cluster 19

These soils are found in climate clusters 3 and 4, on nutrient-medium to rich geology in deep valleys and depressions which give rise to a high water table.

Cluster 20

This profile is found in climate cluster 4, and is common throughout the Walls of Jerusalem, Ben Lomond, Hartz Peak and Central Plateau in waterlogged valleys and flats on the nutrient-rich Jurassic dolerite.

Cluster 21

These soils occur in topographic depressions, flats and valleys under buttongrass moorland which is frequently burned and often waterlogged in climate clusters 1, 2, 4 and 5.

Cluster 22

These soils are found predominantly in climate clusters 4 and 5, on nutrient-poor geology under buttongrass moorlands or alpine sedgelands, on flats or valley floors.

Cluster 23

These profiles are found under buttongrass moorland on nutrient-poor geology, but under minerotrophic flowing water, near creeks or in a nutrient-rich geology near flowing water. This profile cluster occurs under climate clusters 1 and 5.

4.4 Discussion

The organic soil clusters are characterised by a number of environmental factors, which, not surprisingly, are those factors generally found to dominate soil forming processes (Jenny 1941): vegetation, climate, time, parent material and topography. Vegetation was measured on an ordinal scale, representing succession after fire and, together with vegetation height and burn frequency, form the dominant environmental variables, which suggests that the soil clusters are strongly characteristic of the vegetation under which they are found. The vegetation type vector and contours trend in the same direction as soil organic carbon and total nitrogen content in ordination space with a higher soil organic carbon and total nitrogen content content under rainforest and related scrub than on the moorlands. This trend has also been noted in successional stages from mire to forested sites in Finland (Minkkinen and Laine 1998) and long-term soil carbon gains have been found under afforested plantation soils (Lal 2001). An increase in total soil nitrogen has also been found across successional stages in southern Germany from open fen to woodland soils (Waughman and Bellamy 1980).

The Tasmanian forest vegetation communities on organic soils produce a well drained, fibric, reddish organic soil. Alpine vegetation and rainforest experience low frequency burning. High burn frequencies produce moorland vegetation. Burn frequency is high in well-humified organic soils with poor drainage and a permanent water table, with lower burn frequencies occurring on well-drained, fibric soils with no water table. The relationship between burning and paludification has been discussed in the northern hemisphere. Burning has been used as a management tool on mires in Britain and the USA to maintain wetlands and prevent succession of woody species, thus maintaining poor drainage and high water tables (Chapman and Rose 1991, Bowles *et al.* 1996). Human disturbance in the form of woodland removal, especially through burning (Smith and Cloutman 1988) has been thought to cause peat formation in Britain (Moore 1975). Peat formation through frequent burning is thought to occur as a result of poor drainage through soil pore blocking (Mallik *et al.* 1984) by charcoal particles, which also encourages surface runoff. An increase in runoff will result in wetter depressions and drier upper, and, especially, convex upper slopes (Ruhe 1956, Pennock 1997, Pennock *et al.* 1997). This effect of burning on drainage and run-off may be seen in Tasmanian organic soils with a more permanent water table, a more humified and poorly-drained organic soil type found in depressions and valleys than on slopes. The relationships between the organic soil types and the environmental factors of altitude, geology and climate are complex in that there is a strong geographic separation of geology which results in the Precambrian quartzite low-nutrient sites occurring on the western and southwestern part of the State and the Jurassic dolerite, nutrient-rich sites occurring in the central and eastern part of the State. The large majority of the nutrient-rich sites found on Jurassic dolerite occur at altitudes over 750 m a.s.l. The separation of organic soils therefore follows a strong west / east trend, with eastern organic soil types on Jurassic dolerite occupying the lower section of the ordination plot (Figure 4.3.1) (for example, clusters 19 and 20), and western organic soil types on low-nutrient geology in the southwestern and western part of the State (for example, clusters 5, 6 and 10).

4.4.1 Soil-forming processes

4.4.1.1 Parent material

Organosols and organic matter accumulation were found to occur predominantly on Precambrian metamorphosed quartzitic sediments in the west and south west of Tasmania, with limited accumulation on sandstones and Jurassic dolerite. There is a climatic and geographic co-incidence of geology, with Precambrian metamorphosed quartzitic rocks largely occurring in the moist west and south west of Tasmania and Jurassic dolerite in the less moist central and eastern part of the State. Even in areas with high rainfall, the fertility and weatherability of Jurassic dolerite leads to mineral soil development, except in localised depressions where washed in clays have been deposited and impede drainage. Organic soil development on granite and sandstone is also limited, with fibric soils occurring where vegetation productivity is high and an acidic litter horizon has built up over time. Mineral soil development occurs where the Precambrian metamorphics contain phyllites, or where phyllites are concentrated in depressions and gullies through deposition from weathering and subsequent removal of the finer, argillic sediments in the upper catchment. Glacial and periglacial gravels can provide mixed fertility substrate to outwash basins and flats, where fertility depends on the nature of the transported gravels. Concentrations of higher fertility glacial outwash can produce localised clays and therefore mineral soil development. Holocene sands also provide an unconsolidated substrate on which organic soil development is evident, where initiation of organic soil accumulation has occurred in swales or dune slacks, forming an impervious layer of humified organic material which, in turn, provides an ideal surface for waterlogging and reducing conditions for further organic accumulation. Over time, dune system dynamics may cause the topography of the dune slack or swale to change, but the waterlogging conditions have been set in place and poor drainage conditions continue, facilitating organic matter accumulation.

4.4.1.2 Topography

Topography is important in creating the hydrologically suitable conditions for organic matter accumulation and, on certain occasions, providing protection from dominant fire fronts. Broad- scale generalisations about organic soil accumulation could be made, with deep depressions and closed depressions creating waterlogged conditions, and steep slopes, especially convex, or waning slopes and ridges, causing rapid runoff thereby not providing ideal conditions for continuous organic soil cover. The degree to which topographic extremes influence organic soil accumulation and characteristics will vary depending on fire front direction, past fire history, fire frequency, vegetation type, catchment size, climate and microtopography, discussed below. The only organic soils observed as waterlogged throughout the year and to have a water table within 0.5 metres of the soil surface during summer months were those in topographic depressions or or those soils on, or close to, spring mounds and flushes. The absence of a water table during dry spells, especially in summer has been observed in buttongrass ecosystems in the west and south west of Tasmania (Bridle *et al.* 2003, di Folco unpub. data).

4.4.1.3 Climate

The intrinsic soil characteristics which determine the soil clusters include those characteristics which define organosols in soil taxonomies: organic content, bulk density, humification and depth. There are broad trends apparent in the clusters with shallow, low organic content soil clusters occurring in low rainfall, high temperature areas. Despite the apparent trends, other organic soil forming factors interact with climate. Steep convex slopes with a high fire frequency also give rise to a shallow, low organic content soil in areas of high rainfall and low temperatures. Organic soils occur in marginal climatic regions for organic soil accumulation only where there is sufficient catchment runin, springs or localised waterlogging in depressions. The Central Plateau is the driest organic soil-producing region, but experiences the lowest temperatures. Organic soils occurring on the Central Plateau were localised in water-collecting depressions or locations receiving a consistent geogenous water supply. Coastal organic soil-producing regions also have higher temperatures and lower rainfall than the other climatic cluster regions. Deep organic soils are restricted to low-lying coastal swales and depressions. Organic soils along the coast decrease in organic carbon density with a decrease in rainfall and an increase in temperature, but the influence of topography confuses the effect of climate. Climatic requirements for organic soil development should therefore be carefully considered in terms of the interactive effects of other soil forming factors.

4.4.1.4 Vegetation and fire frequency

Organic soils are found under alpine, sub-alpine, rainforest, wet eucalypt forest, coastal complex, moorland, scrub and non-eucalypt forest. In alpine areas, underlying substrate fertility, exposure to wind and high insolation and fire history have been shown to affect productivity of the vegetation and organic soil development (Kirkpatrick and Dickinson 1984a). Organosols found on siliceous substrates in alpine environments were not confined to topographic depressions, shelves or flushes, which were necessary topographic environments for organic accumulation on Jurassic dolerite. On exposed sites in alpine areas in the west and south west, organic soil development of the depth required for organosol classification, was restricted to crevasses, rock interstices, seepage lines and under cushion plants. At lower altitudes, where fire frequency affects the successional stages from moorland through scrub to rainforest or to wet eucalypt forest to rainforest (Jackson 1968), organic soil development is strongly affected by the nature of the vegetation. In the absence of fire, the accumulation of nutrients through time leads to rainforest development (Jackson 1968, Bowman *et al.* 1986). Infertile substrates can experience compounding infertile conditions, such as waterlogging (non-flushing), and past soil removal through fire and subsequent soil erosion. The length of time required for the accumulation of soil nutrients and succession through to rainforest is longer on infertile sites than on fertile sites (Jackson 1968, Bowman *et al.* 1986). The result of long fire-free intervals on infertile substrates is the development of an increasingly fibrous organic soil, with the roots and litter of the vegetation forming acidic, fibric and highly organic material which accumulates due to the reducing conditions of the acidic plant remains, low temperatures and high rainfall. The effect of a microclimate of low temperatures and high humidity is created as the successional stage progresses. This succession in the vegetation is apparent throughout the west and south west of Tasmania, but to find locations where the vegetation has succeeded from buttongrass to rainforest on purely siliceous material is difficult. It is more common to observe rainforest occurring adjacent to buttongrass, on nutrient rich gravels, localised clays, washed in valley and gully clays from phyllites in the upper catchment, river flanks and nutrient rich substrates. In these situations, where geological units are mapped as nutrient-poor, mineral soil development occurs, showing a resolution limit to the available geological maps It is therefore more common to find rainforest on mineral soils than organic soils throughout the west and southwest (Jackson 1968, Pemberton 1989).

Organic soil development through acid-reducing conditions is important, which has also been noted by Gorham *et al.* (1984). No water table was found under the rainforests in the locations in Table 5.4.3, although the soils were damp and conditions under the rainforest were cool and humid, even during dry summer spells. The corresponding moorlands showed signs of both waterlogging and drought, with well humified soils creating overland flow in wet conditions and cracking visibly in summer drought where vegetation cover was sparse. Low hydraulic conductivity has been observed in many of the soil pits in moorlands in this study, with up to three water tables present in one pit and surface ponding common, where there were drier layers below the surface horizon. Low hydraulic conductivity was not observed in scrub, wet forest or rainforest organic soils.

Fire changes the nature and characteristics of organic soils on nutrient-poor substrates, through vegetation succession and also through creating waterlogged, anaerobic and reducing conditions, especially in water collecting topographies. Where left unburned, the organic soil becomes drier through increased uptake from higher plants, more fibrous and more acidic, so reducing conditions are maintained through the vegetation. Where waterlogging is not maintained and soils dry out for long periods in the summer, fire can pose a threat to soil cover, removing organic soil through burning and subsequent erosion (Kirkpatrick and Dickinson 1984a, Maltby *et al.* 1990, Pemberton 1989). This is especially the case on slopes, where both soil dryness and fire intensities are greater. Organic soils tend to be more fibric on slopes, especially convex slopes, as a result of improved drainage, which leaves them prone to burning (Marsden-Smedley 1998, Marsden-Smedley *et al.* 1999). Soil development is therefore limited on convex slopes in fire prone areas and vegetation does not quickly succeed through to a less pyrogenic vegetation cover before experiencing another fire (Jackson 1968, Bowman *et al.* 1986). Concave slopes, with a more reliable water supply are often protected from fire through a faster succession through to a less pyrogenic vegetation stage. In moorland, scrub, wet forest and rainforest, organic soil characteristics are therefore a result of an interaction of climate, vegetation, fire frequency, geology and topography. The shallow, fibric soils found under forest in coastal areas on infertile substrates are probably an edaphic equilibrium of acidic litter and root accumulation and oxidation. Deeper deposits in coastal areas occur under waterlogged conditions and/or where productivity is higher through favourable climatic conditions for plant growth and the accumulation of nutrients in the form of humus.

Chapter 5

Supervised cluster classification

5.1 Introduction

The unsupervised classification based on intrinsic soil qualities produced clear divisions in the characteristics of organic soils found in this survey. The divisions were predominantly based on organic carbon content, degree of humification, total nitrogen content, pH and depth. In order to predict the location and occurrence of these soil characteristics, it is necessary to consider how the dominant environmental effects found in Chapter 4 affect soil characteristics and how the environment can predict the clusters produced through unsupervised clustering.

There are many possible criteria on which to base classification of organic soils in Tasmania, although measurable and observable soil properties that are characteristic of soil-forming processes have been deemed critical in soil classification (Isbell 2002). The creation of further divisions in the Australian Soil Classification (Isbell 2002) would be of particular use, as it would allow for a widely accepted and accessible format. Common classifications for describing organic soils and organic soil landforms (Chapter 2) have been based on environmental descriptors such as, floristics, vegetation physiognomy, morphology, hydrology, stratigraphy, as well as the chemistry and other characteristics of the organic soil itself (Moore and Bellamy 1974). Classifications of organic soils within national and international soil taxonomies use both soil characteristics and environmental factors in their classification systems (Soil Classification Working Group 1998, Soil Survey Staff 2006, FAO 2006). Other systems use only soil characteristics (Isbell 2002). One of the problems with the agricultural soil taxonomies is that some of the differentiae have been based on characterising soils for uses other than geographic prediction or mapping. An example of this is the attribute of substrate hardness in Soil Taxonomy (Soil Survey Staff 2006) which originated from the need to distinguish degrees of substrate hardness for road-building and engineering, rather than for its effects on the character of the overlying soil (Brasfield 1984). These substrate characteristics have been used in the Australian Soil Classification system for organosols (Isbell 2002), even though substrate hardness has not been shown to be an organic soil characteristic and does not form a major gradient. Rather, substrate fertility and permeability is more important in determining the organic soil character (Moore and Bellamy 1974). Isbell (2002) has stated that the Australian Soil Classification should not be based solely on an assumed genesis, but rather should describe what is there. There is an obvious need to use the environmental variables which are relevant to the development of organic soils in Tasmania, rather than borrow blindly from other systems. There is also a need to reassess the differentiae in use for organic soils in the Australian Soil Classification, as the majority of organosols occur on public, reserved land where the land use is predominantly conservation, rather than agriculture. Therefore, the focus of characterising the soils should be on organic soil-forming factors, rather than their use for development. It is also important that an organic soil classification be spatially predicted from existing spatial data sets and that these are related to the soil-forming processes.

This chapter develops supervised classification based on the significant environmental vectors produced in Chapter 4; climate, edaphic, geologic, vegetation, fire and topographic variables, and on the integrating factor of vegetation alone. It is hoped that the unsupervised clusters produced in Chapter 4 will be describable and predictable in terms of the supervised clusters produced in this chapter.

5.2 Methods

Site selection, sampling and the description of the environmental variables are covered in Chapters 3 and 4.

5.2.1 Environmental characteristics recorded for each soil pit

The rationale behind the environmental factors recorded at each site is provided in chapters 1 and 4. The environmental factors considered are geology, vegetation, topography, altitude, burn frequency and climate. Geology, topography, burn frequency, altitude and climate follow the methods detailed in Chapter 4. Vegetation surveys for each soil pit were carried out using the same methods as detailed in Chapter 4. As well as the ordinal scale vegetation productivity class assigned in Chapter 4, each soil pit was then assigned, on the basis of the vegetation survey, to a broad-scale vegetation type as defined by Harris and Kitchener (2005), a TASVEG mapping unit as defined by Harris and Kitchener (2005) and a floristic unit as defined by Kirkpatrick *et al.* (1995).

5.2.1.1 Broad scale vegetation type

Broad scale vegetation types follow those defined by Harris and Kitchener (2005). Out of the eleven broad groups for Tasmania, organosols were found under 6 groups (Table 5.1). In the initial sampling, only 5 of the groups were sampled, as "n", non-eucalypt forest and woodland was subsumed in both "r", rainforest and related scrub and "s", scrub.

Table 5.1

The broad vegetation types defined by Harris and Kitchener (2005) with coding used in the plots shown in the second column.

vegetation type	*abbreviation*
Highland treeless vegetation	a
Rainforest and related scrub	r
Wet eucalypt forest and woodland	f
Scrub	s
Moorland, sedgeland, rushland and peatland	m
Non-eucalypt forest and woodland	n

5.2.1.2 TASVEG mapping units

There are 158 TASVEG mapping units (Harris and Kitchener, 2005). Only those sites found on organosols as defined by Isbell (2002) were used for analysis, although many more were sampled. The samples not used were found to have a peaty horizon, as defined by Isbell (2002). The number of sampled sites and sample sites used for each mapping unit and a brief description of the mapping unit are given in Table 5.2.

Table 5.2

TASVEG mapping units (source, Harris and Kitchener 2005) showing the total number of samples taken in the field and the total number of soil samples found to contain enough organic material to be used in statistical analysis. The asterisk flags those mapping units where much ground had to be covered to find soil that, visually and texturally, resembled organic material to warrant sampling. Organic soils were not found extensively under such sites in the vegetation unit, but only in favourable topographic conditions for organic accumulation.

TASVEG code		*Brief description*	*Number of organic soil samples*	*Total samples taken*
HCH	*	Alpine coniferous heathland	0	20
HCM	*	Cushion moorland	15	30
HSE		Eastern alpine sedgeland	60	80
HUE	*	Eastern alpine vegetation (undifferentiated)	16	30
HHW	*	Western alpine heath	0	20
HSW	*	Western alpine sedgeland/herbland	33	40
SBM	*	*Banksia marginata wet scrub*	0	20
SLW		*Leptospermum* scrub	10	20
SSC	*	Coastal scrub	0	20
SMM		*Melaleuca squamea* heathland	10	20
SHG	*	Heathland on granite	0	20
SMR		*Melaleuca squarrosa* scrub	13	15
SSW		Western subalpine scrub	10	20
SWW		Western wet scrub	36	40
MBU		Buttongrass moorland (undifferentiated)	19	40
MBS		Buttongrass moorland with emergent shrubs	109	110
MBE		Eastern buttongrass moorland	30	60
MGH		Highland grassy sedgeland	10	20
MBP		Pure buttongrass moorland	29	40
MRR		Restionaceae rushland	73	80
MBR	*	Sparse buttongrass moorland on slopes	53	100
MSP		*Sphagnum* peatland	85	90

TASVEG code	*Brief description*	*Number of organic soil samples*	*Total samples taken*
MBW	Western buttongrass moorland	180	200
MSW	Western lowland sedgeland	57	80
RPF	* *Athrotaxis cupressoides – Nothofagus gunnii* short rainforest	0	20
RPW	* *Athrotaxis cupressoides* open woodland	0	20
RPP	* *Athrotaxis cupressoides rainforest*	10	20
RKF	* *Athrotaxis selaginoides – Nothofagus gunnii* short rainforest	15	20
RKP	*Athrotaxis selaginoides* rainforest	25	30
RKS	* *Athrotaxis selaginoides* subalpine scrub	0	20
RCO	Coastal rainforest	46	60
RLS	*Leptospermum* with rainforest scrub	0	20
RMT	*Nothofagus – Atherosperma* rainforest	81	100
RML	*Nothofagus – Leptospermum* short rainforest	11	20
RMS	*Nothofagus – Phyllocladus* short rainforest	10	20
RFS	* *Nothofagus gunnii* rainforest and scrub	0	20
NLE	*Leptospermum* forest	9	20
NLM	* *Leptospermum lanigerum – Melaleuca squarrosa* swamp forest	0	20
NLA	* *Leptospermum scoparium – Acacia mucronata* forest	0	20
WNL	*Eucalyptus nitida* forest over *Leptospermum*	25	30
WNR	*Eucalyptus nitida* forest over rainforest	27	30
WOL	* *Eucalyptus obliqua* forest over *Leptospermum*	0	20
WOR	*Eucalyptus obliqua* forest over rainforest	18	20
ASF	* Freshwater aquatic sedgeland and rushland	0	30

5.2.1.3 Floristic vegetation units

The floristic vegetation units follow the mapped and described vascular plant communities of Tasmania compiled by Kirkpatrick *et al.* (1995) (Table 5.3).
Only those sites found on organosols as defined by Isbell (2002) were used for analysis, although many more were sampled. The samples not used were found to have a peaty horizon, but were not organosols, as defined by Isbell (2002).

Table 5.3

Floristic units (Kirkpatrick *et al.* 1995) showing the total number of samples taken in the field and the total number of soil samples found to contain enough organic material to be used in statistical analysis. The asterisk flags those mapping units where much ground had to be covered to find soil that, visually and texturally, resembled organic material to warrant sampling. Organic soils were not found extensively under such sites in the vegetation unit, but only in favourable topographic conditions for organic accumulation.

Floristic code		*Brief description*	*Number of samples used*	*Total samples taken*
A2		*Poa gunnii – Danthonia nudiflora* marsupial lawn	40	40
A7	*	*Abrotanella forsteroides – Restio australis* bolster heath	0	20
A8		*Gleichenia alpina – Empodisma minus* fernland	40	40
A16	*	*Ozothamnus hookeri - Richea scoparia* heath	11	20
A21	*	*Donatia novae-zelandiae – Dracophyllum minimum* bolster heathland	0	20
A22	*	*Microstrobos niphophilus – Abrotanella forsteroides* coniferous heath	0	20
A24	*	*Orites revoluta – Olearia ledifolia* heath	6	20
A26	*	*Gleichenia alpina – Abrotanella forsteroides* fernland/bolster heath	0	20
A28	*	*Microcachys tetragona – Helichrysum milliganii* coniferous heath	13	20
A29	*	*Donatia novae-zealandiae – Actinotus suffocata* bolster	0	20

Floristic code	*Brief description*	*Number of samples used*	*Total samples taken*
	heath		
A30	* *Isophysis tasmanica – Dracophyllum milliganii* alpine sedgeland	10	20
A31	* *Dracophyllum minimum – Empodisma minus* bolster heath	3	20
A32	* *Donatia novae-zealandiae – Milligania* bolster heath	7	20
A34	* *Nothofagus gunnii – Richea scoparia* deciduous heath	0	20
A35	* *Eucalyptus vernicosa - Isophysis tasmanica* heath	4	20
A36	* *Nothofagus gunnii – Orites milliganii* deciduous heath	0	20
A40	* *Nothofagus gunnii – Exocarpos humifusus* deciduous heath	0	20
B1a	Standard peat	63	100
B1b	* Standard pebbles	37	100
B2	Wet standard	158	200
B3	Pure buttongrass	29	40
B4	Layered blanket moor	111	120
B5	Southwestern sedgy	95	100
B6	Mossy sand	17	20
B12	* Dry copses	0	20
B13	Wet copses	3	3
B15	Mountain copses	10	20
E7	Pure buttongrass	10	20
E8	Layered eastern moor	20	40
S2	Subalpine coniferous mires	30	30
S3	Buttongrass - *Sphagnum* bogs	10	20
S4	*Richea-Sphagnum* bogs	45	45
NIT0	*Eucalyptus nitida – Anodopetalum biglandulosum – Leptospermum glaucescens* mixed forest	66	80
NIT1	* *Eucalyptus nitida – Pomaderris apetala – Dicksonia antarctica* mixed forest	0	20
WET-NIT 2	*Eucalyptus nitida – Melaleuca squarrosa -Monotoca glauca* wet sclerophyll forest	21	30

Floristic code	*Brief description*	*Number of samples used*	*Total samples taken*
T1.1	*Nothofagus cunninghamii – Eucryphia lucida (Phyllocladus aspleniifolius* over *Anodopetalum biglandulosum*	25	30
T3.1	*Nothofagus cunninghamii - Eucryphia lucida* over *Anopterus gladulosus*	7	20
T7.1	*Phyllocladus aspleniifolius - Nothofagus cunninghamii* (-*Eucryphia lucida*) over *Dianella tasmanica - Trochocarpa cunninghamii - Blechnum wattsii*	10	20
T8.1	*Nothofagus cunninghamii – Phyllocladus aspleniifolius – Eucryphia lucida* over *Cenarrhenes nitida*	10	20
I1.1	*Phyllocladus aspleniifolius – Nothofagus cunninghamii –* Myrtaceae spp. over a diverse tangle with *Agastachys odorata*	11	20
I1.4	*Athrotaxis selaginoides* over a diverse tangle with *Agastachys odorata – Richea scoparia*	15	20
I2.1	*Athrotaxis selaginoides* (*-Diselma archeri*) over a diverse tangle with *Nothofagus gunnii* (*- Archeria serpyllifolia*)	5	20
I4.1	*Phyllocladus aspleniifolius – Nothofagus cunninghamii – Eucryphia lucida – Anodopetalum biglandulosum* over *Trochocarpa cunninghamii – T. gunnii – Prionotes cerinthoides*	3	40
C1.1	* *Nothofagus cunninghamii – Atherosperma moschatum* over *Dicksonia antarctica* and / or *Polystichum proliferum*	5	50
M1.1	*Athrotaxis cupressoides / A. selaginoides* over *Nothofagus gunnii – Richea pandanifolia*	18	50
M5.1	*Athrotaxis cupressoides* over *Sphagnum*	10	20
OBO1001	* *Eucalyptus obliqua – Nothofagus cunninghamii – Anopterus glandulosus – Hymenophyllum flabellatum* mixed forest	18	20
OBO111	* *Eucalyptus obliqua – Melaleuca squarrosa – Monotoca glauca* wet sclerophyll forest	25	30
COC00	* *Eucalyptus coccifera – Orites revoluta – Olearia phlogopappa* subalpine mixed forest	2	20
C32	* *Leptospermum glaucescens – Banksia marginata –*	5	20

Floristic code		*Brief description*	*Number of samples used*	*Total samples taken*
		Westringia brevifolia heath / scrub		
FF1	*	*Leptospermum nitidum* closed forest	0	20
FF2	*	*Leptospermum glaucescens – Leptospermum scoparium* closed forest	0	20
F1		Depauperate tea-tree scrub forest	72	80
F2		Depauperate tea-tree / paperbark scrub forest	20	20
F3	*	Tea-tree mesophytic scrub forest	0	20
D4d	*	Heathy *Eucalyptus nitida* woodland	5	20
W22	*	*Baumea arthrophylla* sedgeland	0	10
W24	*	*Carex gaudichaudiana* sedgeland	0	10
W32	*	*Lepidosperma longitudinale* sedgeland	0	10

5.2.2 Exploratory analysis

The environmental variables are those outlined in Chapter 4. The environmental variables were used to determine the supervised cluster centres and were standardised so the values were minimum 0 and maximum 1. Kruskal's non-metric, multidimensional scaling (NMDS) was performed on the euclidean distance matrix of the data using the MASS package in R 2.2.1 (2005). To ensure that the scaling did not converge in a local minima, the NMDS was performed from 100 random starts (10,000 iterations) before a stable solution was accepted. Up to 5 dimensions were used initially, before a 2 dimensional solution was accepted based on low stress of 10.53% and a stressplot of stress against the distance matrix. This allows for a visualisation of the interaction between the environmental variables that, in turn, allows for decisions on the variables used to separate the data into groups for clustering.

5.2.3 Statistical analysis

Cluster analysis has been used to confirm and develop conceptual schemes for grouping soils (for example; Campbell *et al.* 1970, Norris 1972, Langhor *et al.* 1976) and more recently cluster analysis been found to provide soil groupings that are more highly correlated with the natural distribution of soil attributes than hierarchical taxonomic classes (Edmonds *et al.* 1985, Young and Hammer 2000). In Australia, cluster analysis has been used in the predictive classification of soils (McBratney and de Gruitjer 1992, McBratney 1994, Mazaheri *et al.* 1995).

The data were grouped, first by geology, followed by broad vegetation type and then topography. Each group was assigned a cluster number and the centroids for each cluster number were calculated for the intrinsic soil properties described in Chapter 4. All data analysis was performed using the computing system for computational statistics and graphics R 2.2.1. A number of clustering algorithms were performed on the cluster centroids and the resulting clusters were superimposed on the NMDS plot of the intrinsic soil properties produced in chapter 4. The kmeans algorithm as given by MacQueen (1967) was used, using the MASS package (Venables and Ripley 2005) in R 2.2.1. The algorithm works by repeatedly moving all cluster centers to the mean of their respective Voronoi sets. A hard competitive learning clustering algorithm was used, using the mclust package (Fraley and Raftery 2006) in R 2.2.1, which works by randomly drawing an observation from the matrix and moving the closest centre towards that point (Ripley 1996). A neural gas algorithm by Martinetz *et al.* (1993) was used, using the mclust package in R 2.2.1, which is similar to hard competitive learning, but in addition to the closest centroid also the second closest centroid is moved in each iteration. A *c*means fuzzy clustering method was performed on the distance matrix, using the e1071 package (Dimitriadou and Hornik 2006) in R 2.2.1, which is a fuzzy version of the known kmeans clustering algorithm as well as an on-line variant, unsupervised fuzzy competitive learning (Chung and Lee 1992, Nikhil *et al.* 1996). The clusters produced from the various methods were then superimposed on the NMDS plot and visualised until the clusters matched, as close as possible, the separations visible on the plot. To look at the ideal number of clusters in the data, mosaic plots were produced to look at the amount of overlap between the environmental variable clusters and the intrinsic soil variable clusters (the supervised clustering and unsupervised clustering) and necessary divisions were made where possible. These subdivisions were obviously restricted to the data collected and consisted of a division from broad vegetation types, to finer resolution vegetation types based on both the TASVEG mapping units and the floristic units. V-fold cross validation was applied to a range of numbers of clusters and the resulting average distance of the observations in the cross validation from their cluster centres was assessed. Based on this, the k-means clustering method was chosen as the model that best fitted the data on the NMDS plot with an optimal 36 clusters based on both the plotting and v-fold cross validation.

To estimate the effectiveness of the environmental variable (supervised) clusters in describing the intrinsic soil clusters (unsupervised clusters), a number of methods were used. For visualisation, the supervised clusters, the floristic vegetation types, the TASVEG vegetation mapping units and the broad vegetation units were superimposed on the ordination plot of the intrinsic soil properties produced in Chapter 4. Mosaic plots were also produced to view overlap of cluster assignation and to compare the effectiveness of the supervised clusters, the floristic vegetation types, the TASVEG vegetation mapping units and the broad vegetation units in separating the unsupervised clusters. Analysis of the effectiveness of the classifications in separating the unsupervised clusters was performed using compare Class in the mclust package of R 2.2.1 which compares classifications via a normalised variation of information criterion (Meila 2002). Multinomial model comparison was performed using neural networks in the nnet package (Venables and Ripley 2002) in R 2.2.1. The supervised cluster vector produced in the k-means clustering for the environmental variables, the floristic units, the TASVEG mapping units and the broad vegetation units were was used as the response variables with the intrinsic soil variables used as the predictors. The models' AIC were compared for the response that best explained the predictors.

5.3.4 Outcome

Finally, a summary of the supervised cluster classes was produced with the unsupervised clusters, floristic units, broad vegetation classes and TASVEG mapping units found in each cluster described. Boxplots, mosaicplots and summary statistics of the intrinsic soil properties and environmental variables for each supervised cluster can be viewed in Appendix 12.

5.3 Results

The soil pits were ordinated to view the interaction of those environmental variables taken at each soil pit site (Figure 5.1, 5.2, 5.3, 5.4). There is clear separation of the sites in geology and burn frequency with topography and vegetation showing separation within primary divisions.

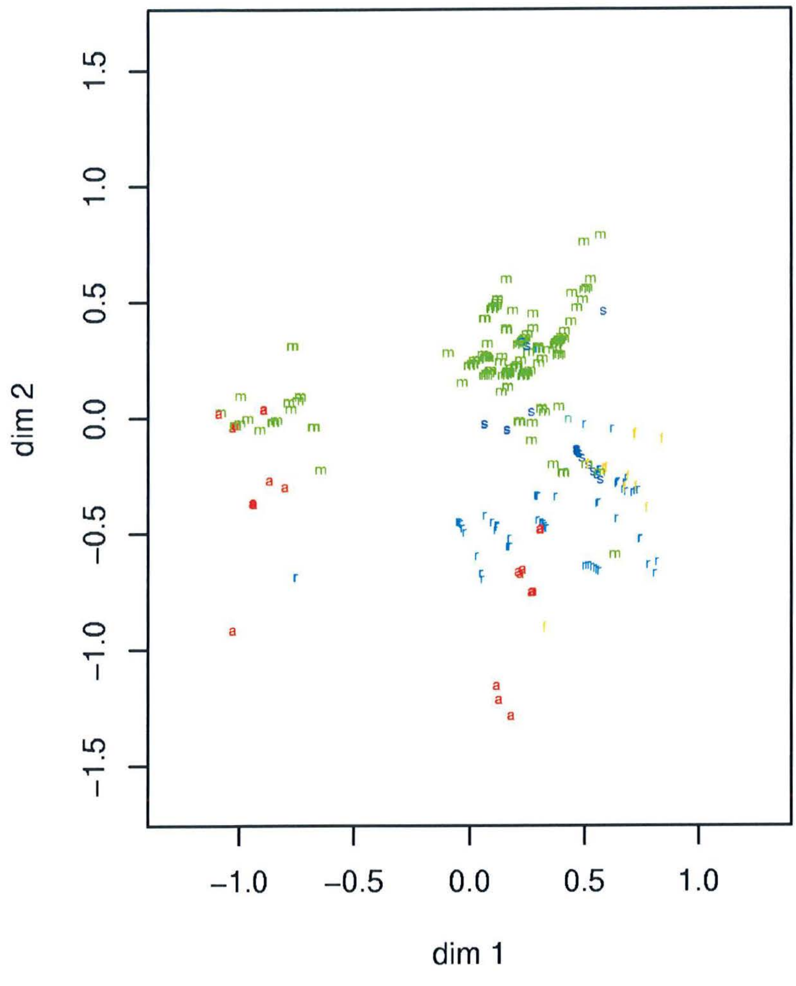

Figure 5.1

NMDS ordination plot with environmental variables highlighted in code. Broad vegetation types (with "a" = alpine, "m" = moorland, "f" = eucalypt forest, "s" = scrub and "r" = rainforest and related scrub). Stress = 8.52%, dimensions = 2, first and second dimension shown as x and y axes respectively.

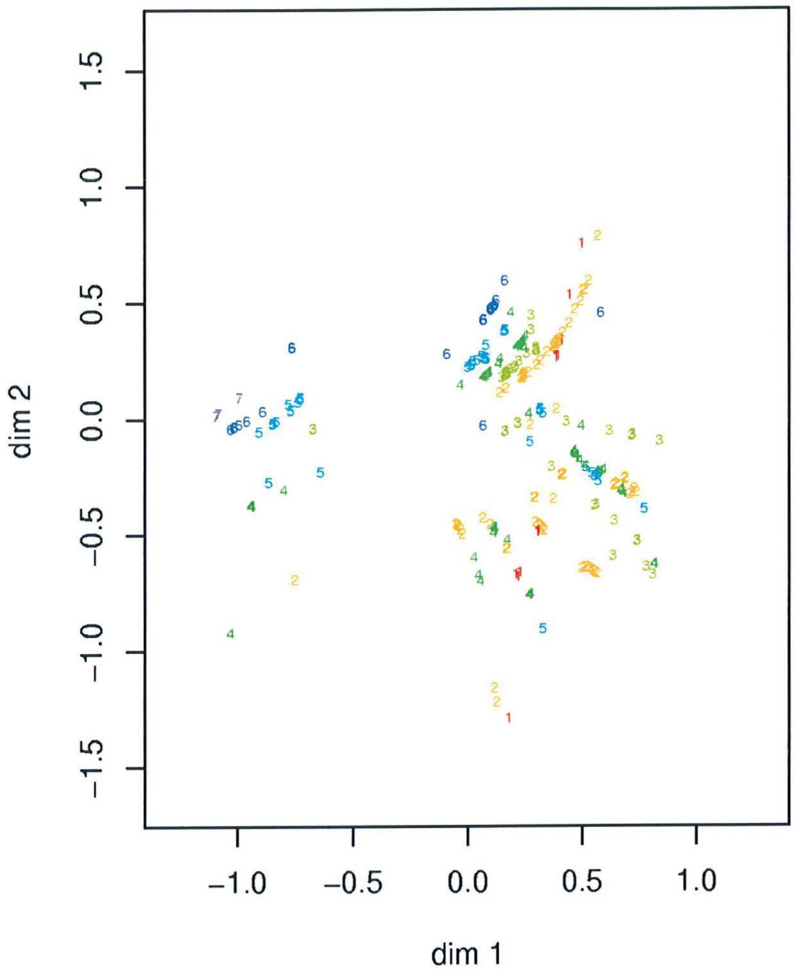

Figure 5.2

NMDS ordination plot with environmental variables highlighted in code. Topography (ordinal scale of 1 to 7 described in Chapter 5 Methods). Stress = 8.52%, dimensions = 2, first and second dimension shown as x and y axes respectively.

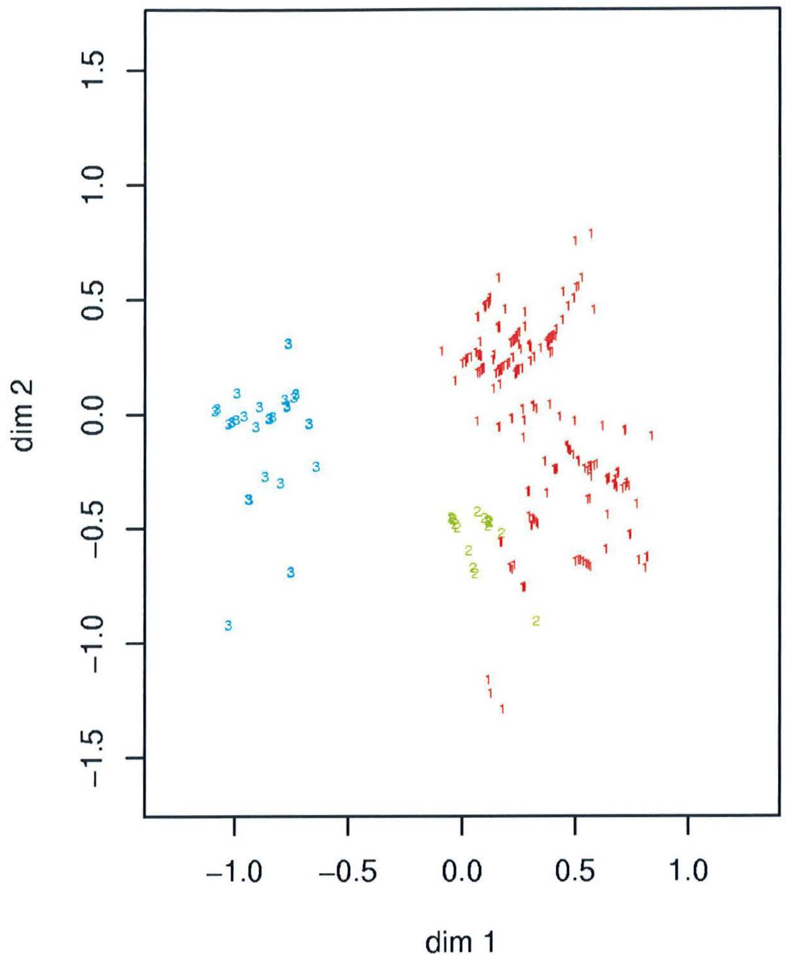

Figure 5.3

NMDS ordination plot with environmental variables highlighted in code. Geology (ordinal scale of 1 to 3 described in Chapter 5 Methods). Stress = 8.52%, dimensions = 2, first and second dimension shown as x and y axes respectively.

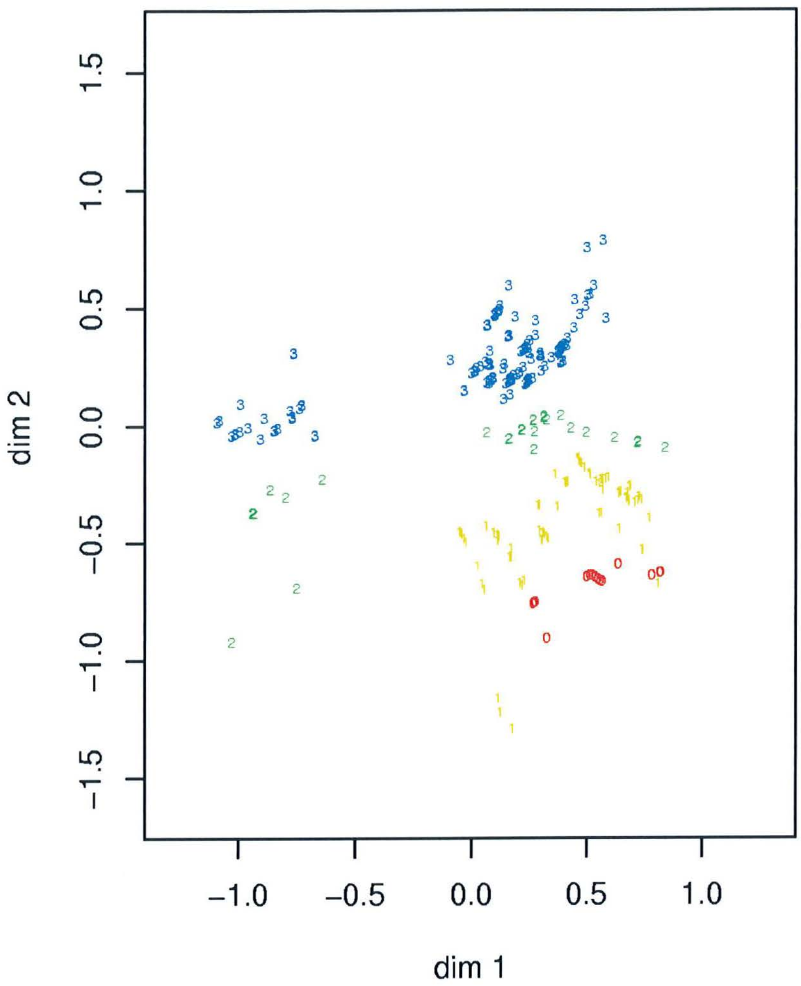

Figure 5.4

NMDS ordination plot with environmental variables highlighted in code. Burn frequency (ordinal scale of 0 to 3 described in Chapter 5 Methods). Stress = 8.52%, dimensions = 2, first and second dimension shown as x and y axes respectively.

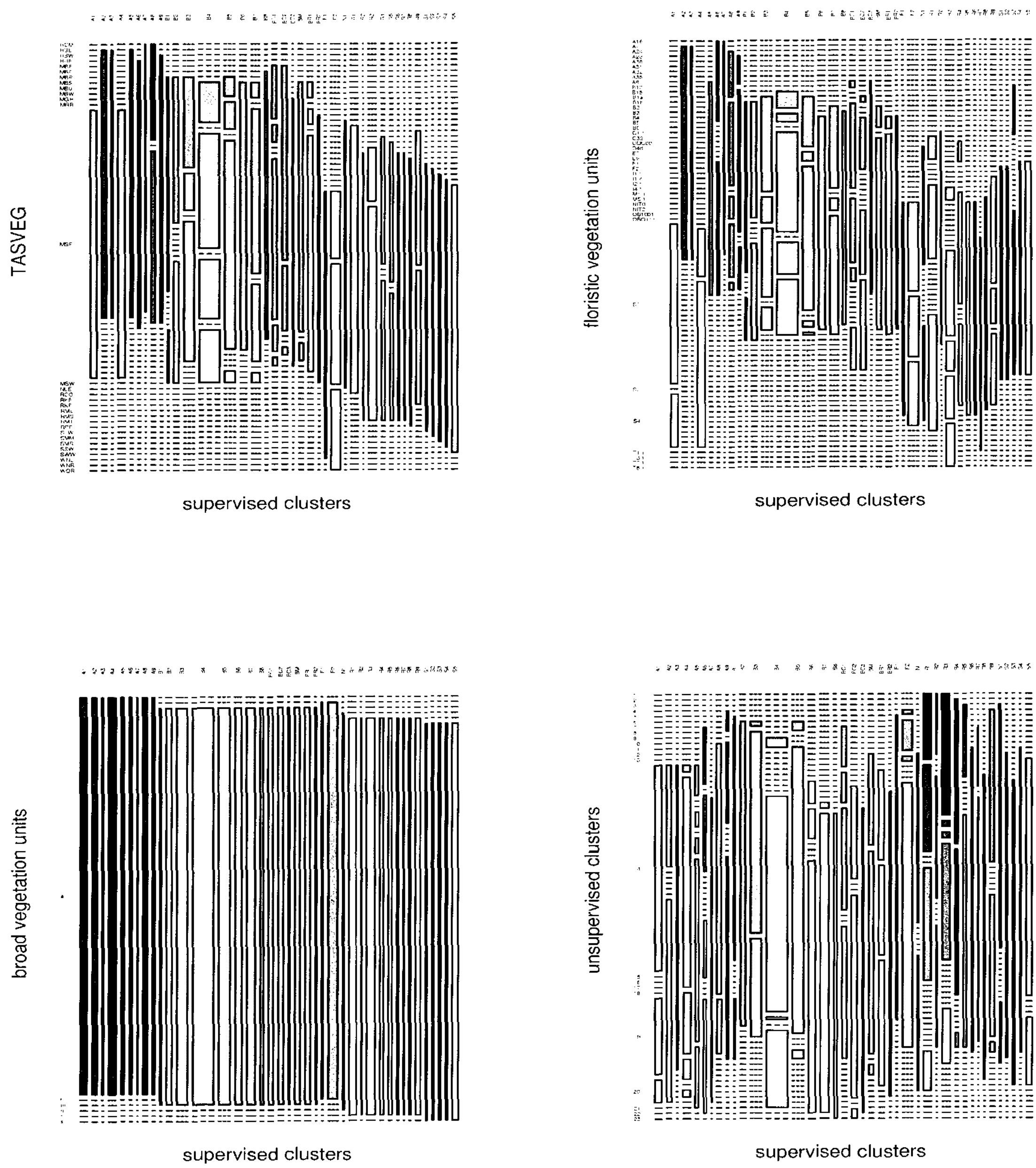

Figure 5.5

Clockwise top left to bottom left, membership of the supervised clusters with the TASVEG mapping units (Harris and Kitchener 2005), the floristic units (Kirkpatrick *et al.* 1995), the unsupervised clusters produced in Chapter 4 and the broad vegetation units (Harris and Kitchener 2005). Codes are explained in the methods section of this chapter. The areas of the rectangular regions are proportional to the number of observations in each group.

As certain broad vegetation types are found across geological type, the initial choice for grouping the data was based on broad vegetation type, followed by geology within those groups, followed by topography within those groups. Further separation of the vegetation types was necessary to represent climate differences, mostly related to altitude. The resulting clusters (Table 5.4) represent only the data in the present study and it is expected that organosols may be found under other vegetation types.

For those sites found on Jurassic dolerite, few topographic divisions were necessary. Few vegetation types on Jurassic dolerite were found to hold organosols, with the exception of the alpine communities. More divisions were necessary on those sites found on nutrient-poor geology as more vegetation types were found to have organosols under them and the range of topographic positions under which organosols were found on nutrient-poor geology was greater than in the case of dolerite. The Jurassic dolerite alpine divisions follow Kirkpatrick's (1997) alpine plant communities and Whinam's work on *Sphagnum* communities (1990). The authors note that the plant communities are associated with water regime, with *Sphagnum* requiring constant moistness and flushing and alpine sedgeland forming a community between the flushed *Sphagnum* and drier alpine heath (Kirkpatrick and Whinam 1988, Kirkpatrick 1997, Whinam 1997). Bolster communities are microtopographic features which accumulate organic matter underneath them and can also act as dam walls, ponding water around them, creating micro-hydrological features and locally raised water levels (Kirkpatrick and Gibson 1984, Kirkpatrick *et al.* 1985). Bolster heath is considered separately, as organic matter was often found to occur only under the bolster itself or as a result of the bolster's damming effect.

Rainforest divisions follow Jarman *et al.* (1984, 1991, 1994) classification of callidendrous, thamnic, implicate, dwarf littoral and montane, with callidendrous found on nutrient-rich sites, while thamnic and implicate are found on nutrient-poor sites, with implicate occupying the poorest sites (Brown *et al.* 1990). Montane rainforest is found at altitudes over 800 m, and is characterised by its species composition, while dwarf littoral rainforest (coastal rainforest) occupies sites close to the coast and is identified by species composition and structure (Jarman *et al.* 1991, 1994).

The association between the supervised cluster and the other vegetation classifications can be viewed in Figure 5.5, with the supervised clusters coinciding with the broad vegetation types (Harris and Kitchener 2005) used as the primary division. Concurrence between the supervised clustering and the TASVEG (Harris and Kitchener 2005) and floristic vegetation types (Kirkpatrick *et al.* 1995) is not perfect, with the poorest correlations occurring between the unsupervised clusters and the moorland vegetation types.

Table 5.4

The divisions are made on broad vegetation type (Harris and Kitchener 2005), underlying geology, topography and relief using the topographic code described in the methods section of this chapter, microtopography from observations in the field and further vegetation divisions described by in both Harris and Kitchener (2005) and Kirkpatrick *et al.* (1995).

Broad Vegetation Types	*Geology*	*Topography and topography code*	*Microtopography*	*Vegetation- further divisions*	*Supervised clustering code*
Highland treeless vegetation	dolerite	slopes and gentle slopes within valleys (6) (7)	minerotrophic flush - sloping fen	*Sphagnum*	A1
				sedge	A2
		spring mounds in deep depressions or valleys (6) (7)	minerotrophic spring – spring fen		A3
		deep depressions or valleys (5) (6) (7)	minerotrophic flushing and waterlogged	*Sphagnum*	A4
				sedge	A5
		hill top flats, shelves or broad flats (4)		sedge	A6
				bolster heath	A7
	quartzite	Slopes, hill top flats, shelves or broad flats (2) (3) (4)		sedge	A8
				bolster heath	A9

Broad Vegetation Types	*Geology*	*Topography and topography code*	*Microtopography*	*Vegetation- further divisions*	*Supervised clustering code*
Moorland	dolerite	lower slopes and valleys (3) (5) (6)	broad flats, valleys	Buttongrass	BC1
			depressions and valleys		BC2
			lakeside or streamside inundation		BC3
	quartzite	steep slopes (1)	upper slopes		B1
		steep slopes (2)	mid slopes		B2
		gentle slopes (3)	convex lower slopes and gentle slopes		B3
		shelves (4)	not isolated, receives runoff		B4
		broad valley bottoms (5)	gentle slopes, gravel rises in broad valleys or sandar		B5
		shelves (4)	shelves and crevasses in between and behind boulders		B6
		valleys depressions (6)	deep valleys or localised depressions		B7
		valleys (5)	river inundation		B8
		broad valleys , sandar (5)	mound forming		BM
	quartzite and sandstone	depressions (5) (6)	depressions and deep depressions	Restionaceae	BR1
	sands	depressions (6)	sands - swales		BR2

Broad Vegetation Types	*Geology*	*Topography and topography code*	*Microtopography*	*Vegetation-further divisions*	*Supervised clustering code*
Scrub	sands quartzite	broad flats, valleys (4)	coastal sand dune system – sometimes buried soils		S1
	quartzite	depressions and valleys (6)			S2
	sands	valleys, swales, depressions (4) (6)	coastal swales and depressions		S3
	quartzite	slopes (3)			S4
	quartzite	broad valleys, sandar (4)	mound forming		S5
Forest – non-eucalypt	quartzite	low relief (4) (5)			N1
Eucalypt forest	sandstone and granite	low relief (4)			F1
	quartzite with phyllites	valleys and depressions(6)			F2
	quartzite and sands	Various			F3

Broad Vegetation Types	*Geology*	*Topography and topography code*	*Microtopography*	*Vegetation-further divisions*	*Supervised clustering code*
Rainforest	quartzite	gentle slopes, flats, broad valleys (3) (4)	low altitude, low relief, coastal	coastal	R1
				callidendrous	R2
				thamnic	R3
				implicate	R4
		slopes (2)		mixed forest	R5
		gentle slopes and valleys (3)			R6
	quartzite with phyllites	valleys and depressions (4) (5) (6)			R7
	dolerite	valleys and gentle slopes (3) (4) (5)		montane	R8
	quartzite	slopes and shelves (2) (3) (4)			R9

Figure 5.6 shows, that the supervised technique provides an adequate method of predicting organic soil characteristics from the proximity in ordination space of the labelled supervised cluster groups. Both broad vegetation types, at a low data resolution, and supervised clusters, at a higher data resolution seem to be able to describe underlying soil characteristics. The directions of the intrinsic soil variables used in the ordination can be seen in Figure 3.1. Soils on the right of the plot are redder in chroma, deep, high in both carbon and nitrogen and are well-drained, supporting rainforest communities which grade to wet eucalypt forest and scrub with poorer drainage and higher water tables. The driest soils, at the base of the plot, are on sands, supporting coastal rainforest and eucalypt forest communities.

Well-drained shallow soils with low organic content are found on the left of the plot on buttongrass moorland communities on slopes, grading to the more humified, wetter soils towards the centre of the plot, also under buttongrass communities. Deep, well humified soils, high in organic content with a high water table are found at the top of the plot under sedge, alpine sedge and *Sphagnum* communities in topographic depressions.

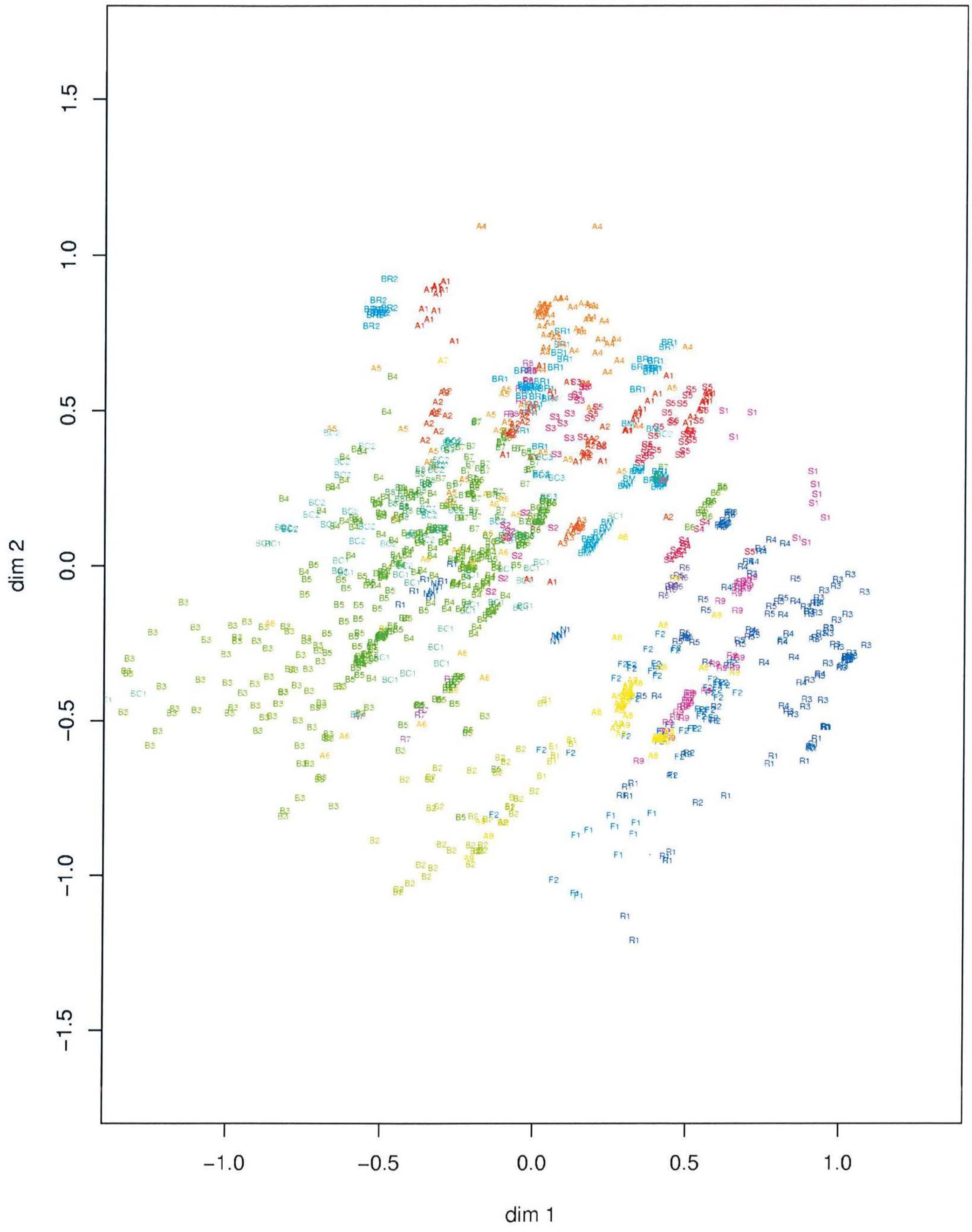

Figure 5.6

NMDS plot of the intrinsic soil variables described in Chapter 4 with the data points used in the clustering for this chapter, labelled as supervised cluster groups. Stress = 10.57%, dimensions = 3. The labels are explained in Table 5.2.1. Colours are assigned to each cluster number for enhanced visualisation using a rainbow colour wheel from red to violet.

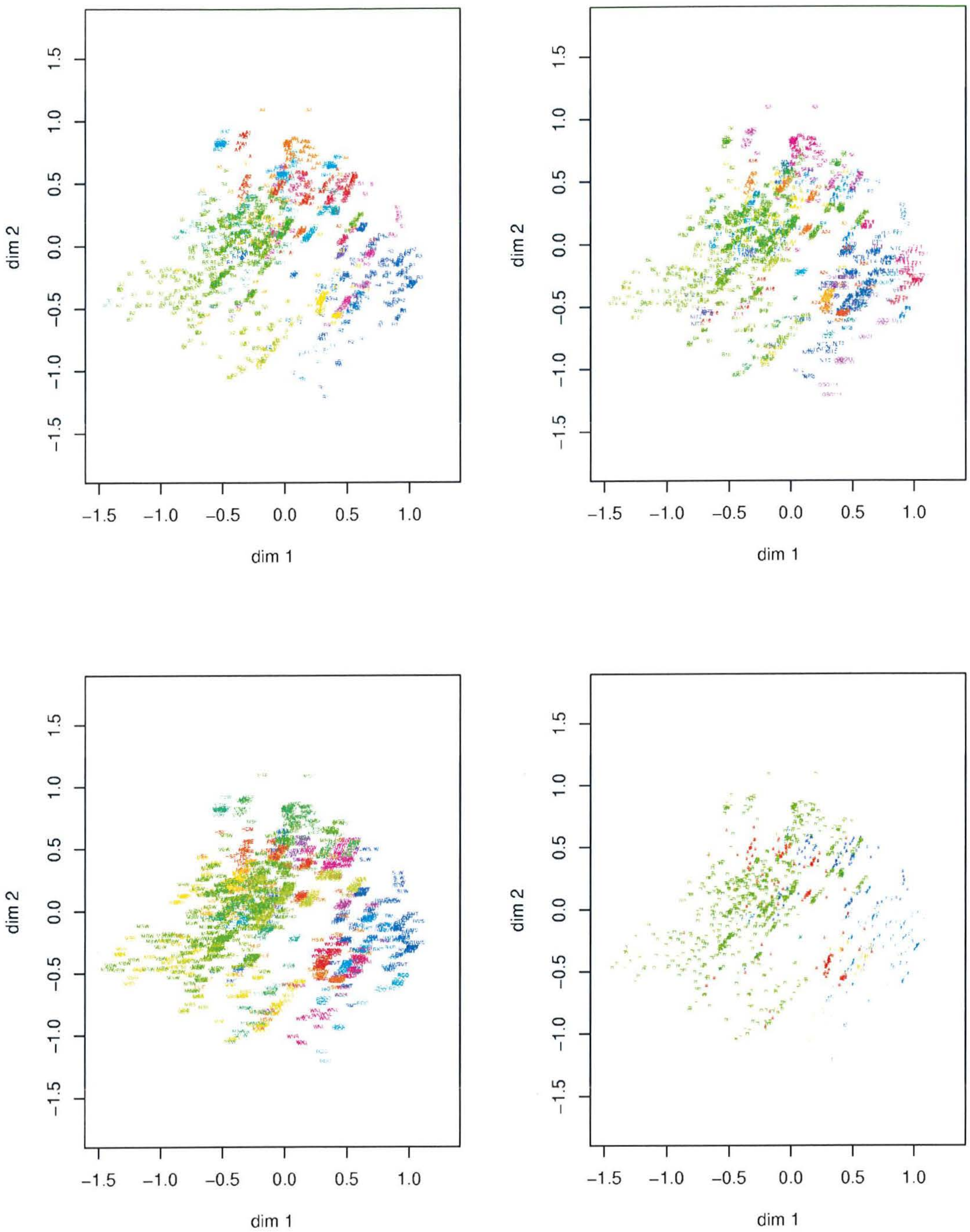

Figure 5.7

NMDS plots of the intrinsic soil variables described in Chapter 4 with the data points used in the clustering for this chapter, labelled as follows, from left to right, top to bottom; supervised cluster groups, floristic units, TASVEG mapping units, TASVEG broad vegetation units. Stress = 10.57%, dimensions = 3, with the first 2 dimensions plotted on x and y axes respectively. The labels are explained in Table 5.1, 5.2, 5.3 and 5.4. Each group is assigned a colour for enhanced visualisation following a rainbow colour wheel from red to violet.

The rainforest sites appear on the right of the plot on soils that are redder, deep, high in both carbon and nitrogen and are well-drained.

To visualise the comparison of the performance of the supervised clustering technique and the use of vegetation alone as an indicator of underlying soil characteristics, four plots of the unsupervised ordination have been produced labelled with the broad vegetation types, the TASVEG mapping units, the floristic units and the supervised cluster groups. This shows the supervised technique as the better descriptor in terms of intrinsic soil characteristics (Figure 5.7). The broad vegetation types, TASVEG mapping units and floristic units do not discriminate soils found under moorland well and the eucalypt forest, scrub and rainforest communities were spread out on the plot. The division of these communities using geology and topography better describes the soil characteristics found under the supervised clusters (Figure 5.7 and Figure 5.8).

The performance of the classifications based on vegetation types were compared with respect to predicting the unsupervised clusters produced in chapter 4 and the intrinsic soil characteristics used to produce the unsupervised clusters in chapter 4. A normalised information criterion method on the broad vegetation type, the TASVEG mapping units, the floristic units and the supervised clusters and their predictive performance on the unsupervised clusters show the supervised clusters to provide the best model (Table 5.5). The same four models were also compared in their ability to predict the soil characteristics used in the unsupervised technique in chapter 4, with the supervised model providing the best prediction through comparison of Akaike's information criterion of the multinomial, log-likelihood model (Table 5.5)

Table 5.5

Four classifications based on vegetation types and their performance in predicting the unsupervised clusters (normalised information criteria) and soil characteristics (AIC and multinomial deviance). The lower the value, the better the performance.

model	*normalised information criterion*	*AIC*	*multinomial deviance*
Supervised cluster groups	0.24	1025	99
TASVEG mapping units	0.39	1453	210
Floristic units	0.39	1545	206
Broad vegetation units	0.40	1381	250

The performance of the four, vegetation-based models in predicting the unsupervised cluster groups can be visualised in Figure 5.8, with the supervised clusters showing the best match with the unsupervised clusters.

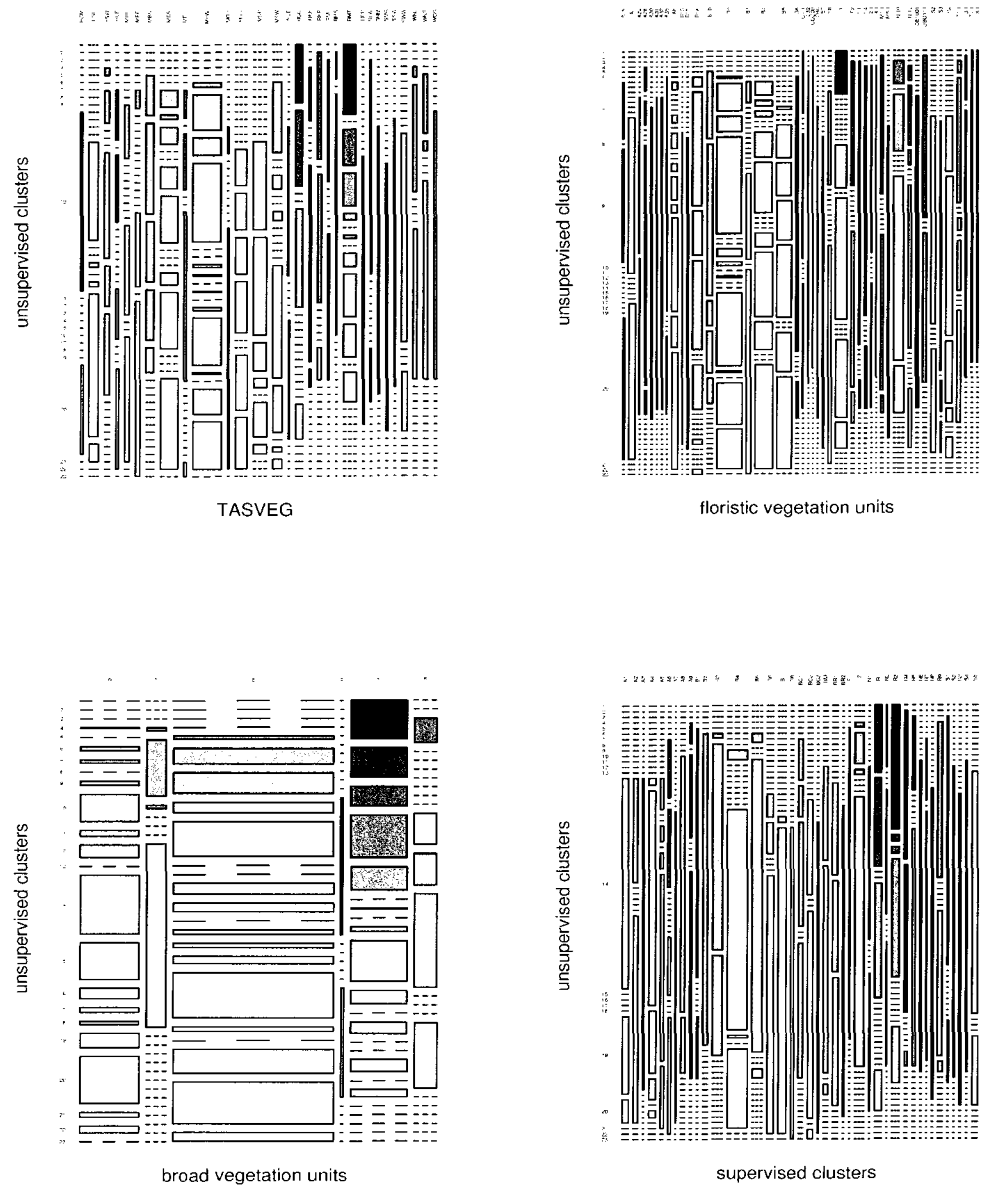

Figure 5.8

Mosaic plots clockwise from top left bottom left of matching between the unsupervised clusters produced in chapter 4 and the supervised clusters produced in this chapter, the TASVEG mapping units (Harris and Kitchener 2005), floristic units (Kirkpatrick *et al.* 1995) and the broad vegetation units (Harris and Kitchener 2005). The areas of the rectangular regions are proportional to the number of observations in each group.

There are a few supervised cluster groups that match the unsupervised groups perfectly (A3, A7, A9, B2, B8, BC3, BR2, F1, R6, R8, S2, S3 and S4) and if the unsupervised cluster groups follow the suggested decision tree in Chapter 4, the supervised cluster groups A2 and B7 would also be perfect fits.

The poorest fits are A5, A6, B1, B4, BC1, F2, R1 and R2 with the variation occurring mostly in carbon and nitrogen content, pH and depth. The similarity of the unsupervised clusters is a matter of choice, depending on which soil characteristics or combination of soil characteristics are of interest to the user. For this purpose, a series of box and mosaic plots for each soil and environmental characteristic in terms of the supervised cluster groups can be viewed in Appendix 12. The main characteristics of the supervised cluster groups are described below and summaries of each group are provided in Appendix 12.

The following is a description of the supervised cluster groups summarised in Table 5.4

Alpine – treeless vegetation

Sphagnum flushes (A1)

This group was found on Jurassic dolerite, but has also been reported to be found on sandstone outcrops on the Central Plateau (Whinam 1990). The group corresponds with TASVEG mapping units, MSP, floristic units S2 and S4 and is under the broad vegetation class moorland. This group is found on gently sloping ground in valleys and depressions where the water table is maintained at or near the surface for most of the year through minerotrophic run off from springs and flushes (see Plate 5.1). The soil is high in organic carbon (average 35%), deep (between 0.5 and 2.5 m), with a nitrogen content of around 1.6% and a pH of around 3.87 reflecting the minerotrophic status of the water. Example locations are on the Central Plateau at King Solomon's Jewels, Walls of Jerusalem and Dixon's Kingdom. This group is found in climate region 2. Unsupervised soil clusters found under this group are 14, 19 and 20.

Plate 5.1

A1 - *Sphagnum* flushes. Walls of Jerusalem, Central Plateau.

Eastern sedge springs and flushes (A2)

This group was found on Jurassic dolerite. The group corresponds with TASVEG mapping unit HSE, floristic unit A3 and belongs to the broad vegetation class moorland. The group is found in a similar topographic and hydrologic position as A1, but is usually around the edge of the *Sphagnum,* forming a boundary between the *Sphagnum* and the non-flushed areas (see Plate 5.2). This group is also characterised by soils with a high organic content, a high water table and soil depths to over a metre. The nitrogen content is around 1%, with a pH of around 4.2 which suggests a minerotrophic water supply. Typical locations are on the Central Plateau at Dixon's Kingdom and along the Lake Loane Track. This group is found in climate region 2. Unsupervised soil clusters found under this group are 14 and 20.

Plate 5.2

A2 - Eastern sedge and spring flushes. Walls of Jerusalem, Central Plateau.

Eastern sedge spring mounds (A3)

This group was found on Jurassic dolerite on the Central Plateau. The group corresponds with TASVEG mapping unit HSE, floristic unit A3 and belongs to the broad vegetation class alpine. The group is found in a distinct topographic and hydrologic position around springs at the bottom of valleys in Jurassic dolerite (see Plate 5.3). The carbon content is high at over 20%, but this is only maintained to a depth of around 0.5 m, where grading to clays occurs. As would be expected, the pH is not as acid as the nutrient poor sites, at 4.11. Minerotrophic water supply is also suggested in the nitrogen content of the soil at 1.4%. A typical location is the Walls of Jerusalem. This group is found in climate region 2. The unsupervised soil cluster found under this group is 14.

Plate 5.3

A3 – Eastern sedge spring mounds. Walls of Jerusalem, Central Plateau.

Sphagnum deep depressions (A4)

This group was found on Jurassic dolerite on and near the Central Plateau and Mount Field. The group corresponds with TASVEG mapping unit MSP, floristic units S3 and S4 and belongs to the broad vegetation class moorland. The group is found in deep depressions, kettle holes, and deep, spring-fed valleys which maintain a high water table with flushing, minerotrophic water (see Plate 5.4). The pH is around 4.43 with an average nitrogen content of 1.4% with the highest nitrogen content measured in the organosols of 2.34%. Depths can reach over 3 m while maintaining a high carbon content of over 35%. Typical locations are the Walls of Jerusalem, King Solomon's Jewels, Pine Valley, Brown Marsh and Mount Field. This group is found in climate region 2.

Unsupervised soil clusters found under this group are 14, 15, 16, 17 and 19.

Plate 5.4

A4, *Sphagnum* in deep depressions, in foreground. A5, Eastern sedge, in deep depressions, in centre. Walls of Jerusalem, Central Plateau.

Eastern sedge deep depressions (A5)

This group was found on Jurassic dolerite on and near the Central Plateau and the Hartz Mountains. The group corresponds with TASVEG mapping unit HSE, floristic unit A8 and belongs to the broad vegetation class alpine. The group is found in depressions on shelves, kettle holes, and deep valleys which are prone to waterlogging, thus maintaining a high water table (see Plate 5.4). The pH is around 4.38 with an average nitrogen content of 1.34%. Depths can reach over 1 m, but vary widely with underlying topography from 0.2 m to over 1 m. Typical locations are the Walls of Jerusalem, King Solomon's Jewels, Central Plateau, Pine Lake and Hartz Mountains. This group is found in climate region 2. Unsupervised soil clusters found under this group are 14, 17, 19, 20 and 21.

Eastern alpine sedgeland (A6)

This group was found on Jurassic dolerite on and near the Central Plateau, Mount Wellington, Ben Lomond, Mount Field and the Hartz Mountains. The group corresponds with TASVEG mapping unit HUE, floristic units A8 and A16 and belongs to the broad vegetation class alpine. The group is found on table top mountains and shelves where drainage and runoff are impeded due to relief or the clay and peat damming effects of vegetation (see Plate 5.5). Carbon contents are lower and vary between 10% and 40%, from organic rich clay to organosol, which is controlled by the microtopography and degree of waterlogging. The water table is also lower and variable throughout the year and consequently organic depths are shallow, between 0.1 m and 0.53 m. The nitrogen content is approximately 0.66% and the pH is approximately 4.05; both values are lower than the minerotrophic, spring-fed soils. Typical locations are the Mount Wellington, Central Plateau, Ben Lomond and Hartz Mountains. This group is found in climate region 2. Unsupervised soil clusters found under this group are 7, 9, 18 and 22.

Plate 5.5

A6 – Eastern alpine sedgeland. Mt. Hugel track near Lake St.Clair.

Eastern bolster heath (A7)

This group was found on Jurassic dolerite on the Central Plateau, Ben Lomond and Mount Field. The group corresponds with TASVEG mapping unit HCM, floristic unit A16 and belongs to the broad vegetation class alpine. The group is found in valleys, table top mountains and shelves where drainage is impeded due to relief or the clay and peat damming effects of vegetation. The bolsters may contribute to the damming effects by providing the dam structure and thus form part of a pool, hummock complex (see Plate 5.6). Bolsters may also occur on rocky outcrops, and due to the microclimatic effects of the bolster itself, form a localised organosol beneath the photosynthesising outer wall. Carbon contents are high at over 40%, with a very low bulk density of 0.18, due to the unhumified remains of the bolster plant under the bolster wall. The nitrogen content is approximately 0.99%, and the pH is approximately 4.23. Typical locations are the Walls of Jerusalem, Central Plateau, Ben Lomond and Hartz Mountains. This group is found in climate region 2. The unsupervised soil cluster found under this group is 20.

Plate 5.6

A7 – Eastern bolster heath. Walls of Jerusalem, Central Plateau.

Western bolster heath (A8)

This group was found on Precambrian quartzite mountains and mountain range in the west and south west of Tasmania. The group corresponds with TASVEG mapping units HCM and HSW, floristic units A24, A28, A31 and A32 and belongs to the broad vegetation class alpine. The group is found on mountains and shelves where drainage is impeded due to relief, although they are found in topographically drier locations than the eastern bolster heath organosols (see Plate 5.7). The bolsters form on quartzite or eroded quartzite gravels and, due to the microclimatic effects of the bolster itself, form a localised organosol beneath the photosynthesising outer wall. Carbon contents are variable between 11% and 48%, as are depths at between 0.1 and 0.5 m. Bulk density was also higher, as the organosol was more humified. The nitrogen content is approximately 0.33% and the pH 3.33. Typical locations are the Tyndall Range and Mount Murchison. Unsupervised soil clusters found under this group are 10 and 11. This group is found in climate region 5.

Plate 5.7

A8 – Western bolster heath. Tyndall Range, western Tasmania.

Western alpine sedgeland (A9)

This group was found on Precambrian quartzite mountains and mountain ranges in the west and south west of Tasmania. The group corresponds with TASVEG mapping unit HSW, floristic units A28, A30 and A35 and belongs to the broad vegetation class alpine. The group is found on mountains and shelves where drainage is impeded due to relief or microtopography. This group is also found in positions protected from fire, such as in crevasses between boulders. Carbon contents vary between 13% and 45%. Depths vary between 0.1 and 0.4 m. The nitrogen content is approximately 0.38% and the pH 3.34. Typical locations are the Tyndall Range, Mount Sprent, Ironbound Range and Mount Murchison. This group is found in climate region 5. Unsupervised soil clusters found under this group are 4, 6 and 12.

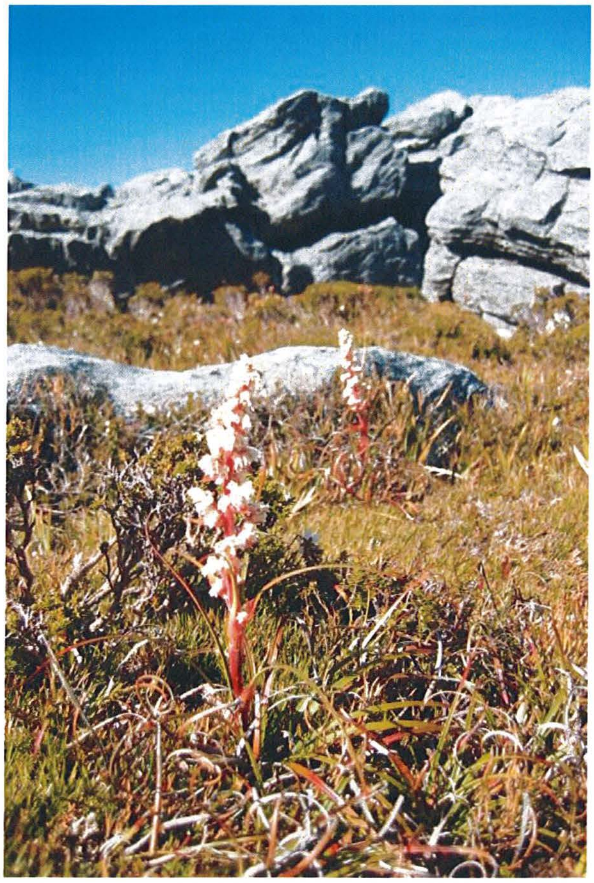

Plate 5.8

A9 – Western alpine sedgeland. Mount Sprent, south west Tasmania.

Buttongrass moorland – *Gymnoschoenus sphaerocephalus* and Restionaceae spp.

Buttongrass moorland on steep slopes (B1)

This group was found on Precambrian quartzite and silica-rich conglomerates on steep slopes and upper slopes throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MBR and MBW, floristic units B6, B1b and Nit2 and belongs to the broad vegetation class moorland. The group is found on isolated slopes with limited run-off, where organic matter accumulation is the result of microtopographic features (see Plate 5.9). These features are scattered across saddles and upper slopes and provide protection of both plants and underlying soil from wind, drought and fire on otherwise exposed upper slopes. The fire protection is in the form of shelter from the prevailing fire front directions through topographic position between boulders and rocky outcrops, which also act as soil accumulating depressions and refuges from insolation, wind and drought. Protection from drought is also offered along seepage lines or areas along a break in slope providing a pathway for runoff, with burrowing crayfish (of genera *Ombrastacoides* and *Spinastacoides*) pools holding water longer than the surrounding slopes. Organic soils are shallow, varying between 0.1 and 0.6 m deep, with carbon contents of between 10% and 41%. The pH is approximately 3.53, with a nitrogen content of approximately 0.23%. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Mount Murchison, Birch's Inlet, Melaleuca, Twelvetrees Range and The Needles. This group is found in climate regions 3 and 4. Unsupervised soil clusters found under this group are 5, 9 and 12.

Plate 5.9

B1 – in background, buttongrass moorland on steep slopes. Tyndall Range, westernTasmania.

Buttongrass moorland on exposed slopes (B2)

This group was found on Precambrian quartzite and silica rich conglomerates on steep slopes and midslopes throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MBR and MBW, floristic units B1a, B1b and B6 and belongs to the broad vegetation class moorland. The group is found on steep, exposed slopes under buttongrass moorland where organic matter accumulation is limited through lack of vegetation cover, drought, fire history or relief. This group is often found on bare slopes where the accumulation of organic soil is sporadic and varies with topographic micro features that favour accumulation by providing protection from the elements (see Plate 5.10). The soils are, therefore, invariably found under vegetation clumps, behind boulders and rocks and in burrowing crayfish pools. This group is distinguished from group B1, in its topographic location on midslopes, away from seepage and drainage lines. It, therefore, has a lower depth and carbon content of around 13% to depths of up to 0.5

m. The acidity, with a pH at around 3.53 and low fertility, with a nitrogen content of around 0.26%, reflects the underlying substrate. Example locations are at Newton Creek, Lake Plimsoll, Lake Julia, Mount Murchison, Birch's Inlet, Melaleuca, Twelvetrees Range and The Needles. This group is found in climate regions 3 and 4. The unsupervised soil clusters found under this group is 6.

Plate 5.10

B2 – buttongrass moorland on exposed slopes. Twelvetrees Range, south west Tasmania.Buttongrass moorland on slopes (B3)

Buttongrass moorland on slopes (B3)

This group was found on Precambrian quartzite and siliceous conglomerates on slopes and lower slopes throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MBR, MBS and MBW, floristic units B1a, B1b, B2, B4 and Nit2 and belongs to the broad vegetation class moorland. The group is found on slopes under buttongrass moorland where organic matter accumulation is limited through lack of vegetation cover, drought, fire history or relief. This group is often found on bare slopes where the accumulation of organic soil is sporadic and varies with topographic microfeatures that favour accumulation by providing protection from the elements (see Plate 5.11). The deeper soils are therefore found under vegetation clumps, behind boulders and rocks and in burrowing crayfish pools. This group is distinguished from group B1 and B2, in its topographic location on more gentle slopes, receiving runoff from upper slopes and therefore experiencing a more reliable water input. The increased runoff also washes in and deposits siliceous sands and erodes soil accumulations on convex slopes. The erosion and deposition of soil results in a varied organic soil depth and carbon content. The soils are often well-humified, hemic or sapric deposits with between 4% and 36% organic carbon content to depths of up to 1 m. The acidity, with a pH at around 3.53, and low fertility, with a nitrogen content of around 0.2%, reflect the underlying substrate. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Mount Murchison, Birch's Inlet, Melaleuca, Twelvetrees Range and The Needles. This group is found in climate regions 3, 4 and 5. The unsupervised soil clusters found in this group are 7 and 8.

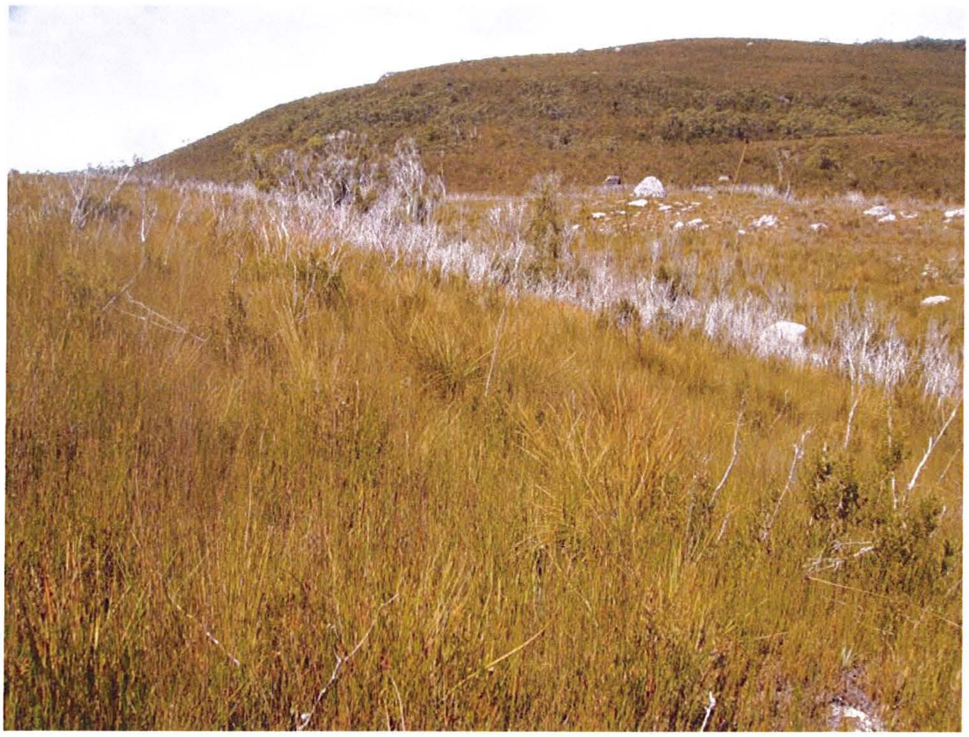

Plate 5.11

B3 – buttongrass moorland on slopes. Newton Creek, western Tasmania.

Buttongrass moorland on shelves (B4)

This group was found on Precambrian quartzite and silica-rich conglomerates on shelves receiving runoff from slopes and lower slopes throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MSW, MRR, MBS and MBW, floristic units B1a, B2, B4, B5 and B15 and belongs to the broad vegetation class moorland. The group is found on shelves under buttongrass moorland where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year (see Plate 5.12). This results in an increased humification, depth and carbon content, depending on microtopography, compared with the surrounding slopes. The soils are often well-humified, hemic or sapric deposits with between 11% and 46% organic carbon content to depths of up to 1.5 m. Microtopographic features, such as localised depressions between boulders and rocks, serve to add variety to depths and organic carbon content. The acidity, with a pH at around 3.55 and low fertility, with a nitrogen content of around 0.36%, reflect the underlying substrate. This group is found in climate regions 3, 4 and 5. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Mount Murchison, Birch's Inlet, Melaleuca, Twelvetrees Range, The Needles and Mount Sprent. The unsupervised soil clusters found under this group are 9, 18 and 21.

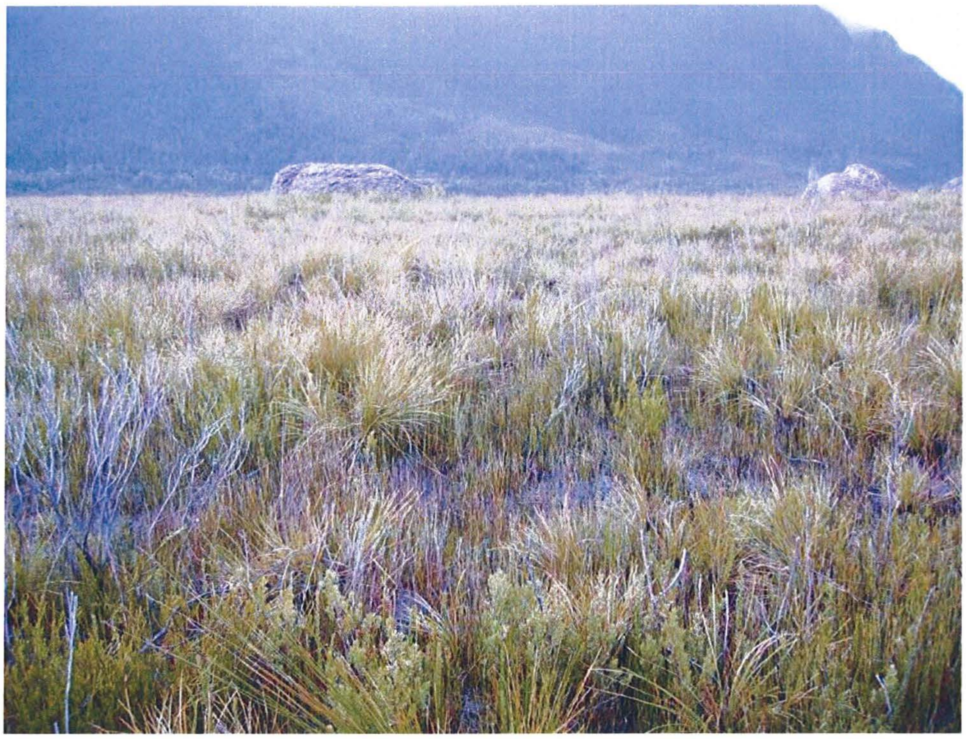

Plate 5.12

B4 – buttongrass moorland on shelves. Twelvetrees Range, south west Tasmania.

Buttongrass moorland on rises in broad valleys and flats (B5)

This group was found on Precambrian quartzite and siliceous conglomerates in broad valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MBR, MBS and MBW, floristic units B1a, B1b, B2, B4, B5 and Nit2 and belongs to the broad vegetation class moorland. The group is found in broad valleys and sandar where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year. This group is found on either gently sloping ground in broad valleys, or on gravel rises within broad valleys, which serve to raise the soil above the permanent water table and water runoff from the surrounding slopes (see Plate 5.13). This results in a water table that is at or near the surface when rainfall input is sufficient, but dries out during prolonged periods without precipitation. Depth and carbon content vary depending on the microtopographic position within the valley. The soils are often well-humified, hemic or sapric deposits with between 6% and 29% organic carbon content to depths of up to 0.9 m. Microtopographic features, such as localised depressions between boulders and rocks, serve to add variety to depths and organic carbon content. The acidity, with a pH at around 3.43, and low fertility, with a nitrogen content of around 0.26%, reflect the underlying substrate. This group is found in climate regions 3, 4 and 5. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Louisa Plains, Birch's Inlet, Melaleuca, Twelvetrees Valley, Edgar Ponds and McPartlan Pass. The unsupervised soil clusters found under this group are 6, 9 and 12.

Plate 5.13

B5- buttongrass moorland on rises in broad valleys and flats (foreground). Louisa Plains, south west Tasmania.

Buttongrass moorland on saddles and boulder slopes (B6)

This group was found on Precambrian quartzite and siliceous conglomerates on slopes and saddles throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit MBS, floristic units B4 and belongs to the broad vegetation class moorland. The group is found on slopes and saddles where there is a consistent water supply. This group is found on either saddles or slopes with protection from fire in the form of rock outcrops or large boulders (see Plate 5.14). Depth and carbon content vary depending on the microtopographic position, but soils are fibric deposits grading to hemic with depth, with between 29% and 49% organic carbon content to depths of up to 1 m. The acidity, with a pH at around 3.39, is notably higher than the surrounding moorland, as is the nitrogen content which around 0.75% nitrogen in the lower horizons and around 1.14% in the upper horizons. This reflects the nature of the accumulating plant material. This group is found in climate region 4. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Melaleuca, Twelvetrees Valley, Edgar Ponds and McPartlan Pass. The unsupervised soil clusters found under this group are 17, 18 and 22.

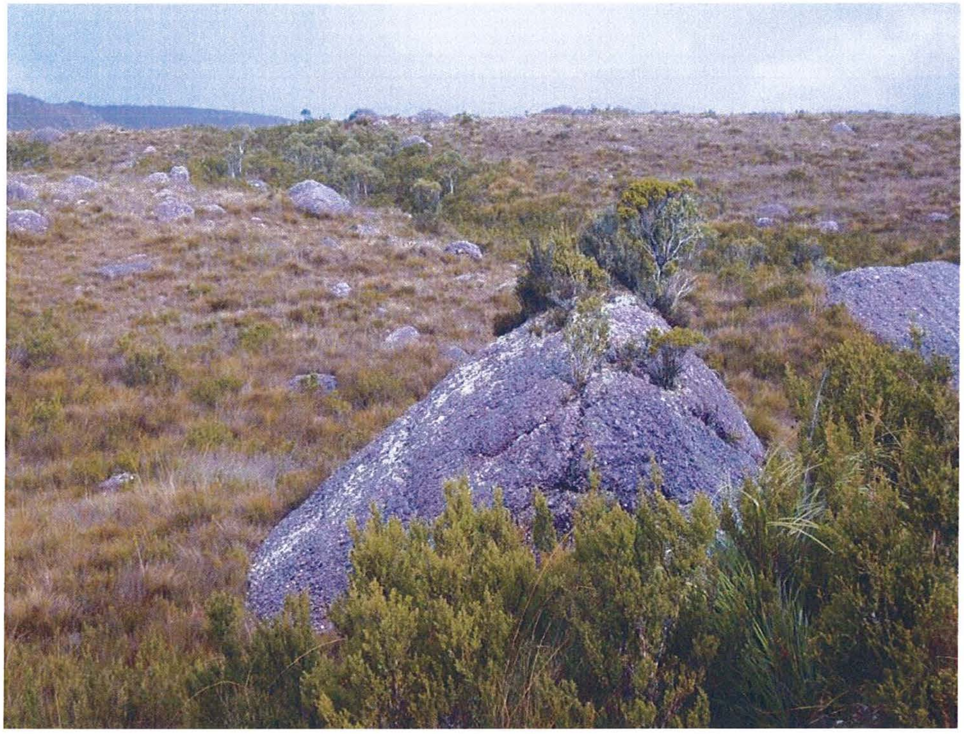

Plate 5.14

B6 – buttongrass moorland on saddles and boulder slopes. Twelvetrees Range, south west Tasmania.

Buttongrass moorland in broad valleys and flats (B7)

This group was found on Precambrian quartzite and siliceous conglomerates in broad valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MRR, MBS, MBW and MSW, floristic units B2, B4 and B5 and belongs to the broad vegetation class moorland (see Plate 5.15). Organic matter accumulation occurs through the maintenance of a high water table for a portion of the year from runoff from the surrounding slopes, or from broad channels between gravel rises within broad valleys prone to waterlogging. This results in a water table that is at or near the surface for most of the year. Depth and carbon content vary depending on the microtopographic position within the valley. The soils are well-humified, hemic or sapric deposits with between 24 and 49% organic carbon content to depths of up to 1 m. The acidity, with a pH at around 3.66, reflects the underlying substrate. There is a slightly higher nitrogen content of around 0.6%, compared with the surrounding slope soil of around 0.2%. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Louisa Plains, Birch's Inlet, Melaleuca, Twelvetrees Valley, Edgar Ponds and McPartlan Pass. This group is found in climate regions 3, 4 and 5. The unsupervised soil clusters found under this group are 21 and 22.

Plate 5.15

B7 – buttongrass moorland on broad valleys. Twelvetrees Range, south west Tasmania.

Buttongrass moorland along drainage lines in valleys and flats (B8)

This group was found on Precambrian quartzite and siliceous conglomerates in broad valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit MBP, floristic units B3 and belongs to the broad vegetation class moorland. The group is found in broad valleys and sandar where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year from inundation by rivers (see Plate 5.16). This group is found on either gently sloping or flat ground in broad valleys close to water channels, often under buttongrass moorland with *Diplarrena latifolia* and *Banksia marginata*. The soils are well-humified sapric deposits with between 16% and 31% organic carbon content to depths of up to 0.6 m. The pH, at approximately 3.65, is the least acidic of the buttongrass moorland groups found on siliceous substrates. Nitrogen content is high, at around 1.02%. This reflects the washing in of nutrients from the upper catchment. Typical locations are Newton Creek, Lake Plimsoll, Louisa Plains, Raglan Plains, Twelvetrees Valley, Edgar Ponds, McPartlan Pass. This group is found in climate region 4. The unsupervised soil cluster found under this group is 23.

Plate5. 16

B8 – buttongrass moorland along drainage lines. Newton Creek, western Tasmania.

Buttongrass moorland accumulating peat mounds (BM)

This group was found on Precambrian quartzite and siliceous conglomerates in broad valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MBW and MBS, floristic units B2 and B4 and belongs to the broad vegetation class moorland. The group is found on gravel rises in broad valleys and sandar where organic matter accumulation occurs through the acidic, reducing nature of the deposits. Gravel rises on sandar provide islands for plant colonisation and the better drainage allows for a rapid succession through from moorland to scrub communities. The organic matter accumulation occurs on better drained gravel rises, producing mounds of organic soils, raised above the level of the surrounding plains. These mounds have a fibric upper horizon on top of more humified deposits, raised above water channels (see Plate 5.17). The pH, at around 3.17 is the lowest of the moorland types found on nutrient poor substrates. Fertility, with a nitrogen content of around 0.96% in the lower horizons and 1.25% in the surface horizons, is higher than the surrounding moorland. Depths are between 0.6 m and 2.2 m. This group is found in climate regions 3, and 4. Typical locations are Newton Creek, Lake Plimsoll, Lake Julia, Louisa Plains, Birch's Inlet, Melaleuca, Twelvetrees Valley, Edgar Ponds, McPartlan Pass. The unsupervised soil clusters found under this group are 12 and 13.

Plate 5.17

BM – mound-forming buttongrass moorland. Louisa Plains, south west Tasmania.

Restionaceous moorland (BR1)

This group was found on Precambrian quartzite and sandstones in deep depressions in valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units MRR and MBS, floristic units B4 and B5 and belongs to the broad vegetation class moorland. The group is found in depressions where organic matter accumulation occurs from a persistently high water table. *Leptocarpus tenax* and *Gleichenia dicarpa* dominate the vegetation (see Plate 5.18). The soils are well-humified sapric deposits with between 41% and 49% organic carbon content to depths of up to 2 m. The average pH of 3.48 is low, although the nitrogen content is often higher than the surrounding moorland, averaging 1.09%. Typical locations are Newton Creek, Raglan Plains, Strahan, Blowhole Valley and Blackhole Valley. This group is found in climate region 4.

The unsupervised soil clusters found under this group are 15, 16 and 17.

Plate 5.18

BR1 – restiad moorland. Raglan Plains, western Tasmania

Coastal Restionaceae moorland (BR2)

This group was found on coastal Holocene sand deposits on the west and south west coast of Tasmania. The group corresponds with TASVEG mapping units MRR and MSW, floristic unit B4 and belongs to the broad vegetation class moorland. The group is found in swales on sand deposits along the west and southwest coast of Tasmania where organic matter accumulation is associated with a persistently high water table, with *Leptocarpus tenax*, *Gleichenia dicarpa* or *Melaleuca squarrosa* dominating the vegetation. The organic soils are well-humified sapric deposits with low bulk densities of around 0.3 kg/m^3. This group is found where there is a throughflow of water in an unconfined basin. Throughflow may be partly responsible for a nitrogen content of around 1.39% in the lower horizons and 1.56%

in the surface horizon. Carbon content is between 38% and 44% to depths of up to 1.5 m. The pH is low at approximately 3.41. Pyrite may be present in the lower horizons. This group is found in climate region 4. Typical locations are Buoy Creek and Strahan. The unsupervised soil cluster found under this group is 19.

Eastern buttongrass moorland in valleys (BC1)

This group was found on Jurassic dolerite in the central highlands area of Tasmania. The group corresponds with TASVEG mapping units MGH, MBE, MBU, MBP and MBW, floristic units B1a, B2, B3, A8 and E8 and belongs to the broad vegetation class moorland. The group is found on the boundaries of depressions and waterlogged valleys on Jurassic dolerite in upland areas of Tasmania (see Plate 5.19). The water table is at or near the surface for part of the year. Well-humified sapric deposits grade to clay with depth, although, where the water flows, the transition can be abrupt. Carbon content is variable, depending on proximity to rocky outcrops, or the basin edge, ranging between 2% and 44% to depths of between 0.1 m and to 1 m. The clay deposits can be up to 1 m thick below the organic material. The pH is approximately 4.18, with nitrogen contents around 0.45. Typical locations are King William Plains, Navarre Plains, Lake St. Clair, Clarence Lake, Snug Tiers, Harlequin Hill flats, Platypus track. This group is found in climate regions 1, 2 and 4. The unsupervised soil clusters found under this group are 7, 8 and 12.

Plate 5.19

BC1 – eastern buttongrass moorland in valleys. Navarre Plains, central Tasmania.

Eastern buttongrass moorland in depressions (BC2)

This group was found on Jurassic dolerite in the central highlands area of Tasmania. The group corresponds with TASVEG mapping units MBE and MBP, floristic units B1a, B3, E7 and E8 and belongs to the broad vegetation class moorland. The group is found in depressions and waterlogged valleys on Jurassic dolerite in upland areas of Tasmania where organic matter accumulation occurs as a result of a consistently high water table (see Plate 5.20). Carbon content is between 9% and 47% to depths of between 0.2 m and 1 m. Well-humified sapric organic soil horizons either grade to clay, or there can be an abrupt horizon between organic soil and clay. The clay deposits can be up to 1 m thick below the organic material. The pH is around 4.22, with nitrogen contents around 0.34%. Typical locations are King William Plains, Navarre Plains, Lake St. Clair, Clarence Lake, Snug Tiers. This group is found in climate regions 1, 2 and 4. The unsupervised soil clusters found under this group are 18, 21 and 23.

Plate 5.20

BC2 – eastern buttongrass moorland in depressions. Lake St.Clair, central Tasmania.

Eastern buttongrass moorland beside drainage channels or lakes (BC3)

This group was found on Jurassic dolerite in the central highlands area of Tasmania. The group corresponds with TASVEG mapping unit MGH, floristic units A8 and S3 and belongs to the broad vegetation class moorland. The group is found in depressions along drainage lines and waterlogged valleys on Jurassic dolerite in upland areas of Tasmania where organic matter accumulation occurs as a result of a consistently high water table. This results in well-humified sapric deposits with lower bulk densities (average 0.5 kg/m^3) than the surrounding moorland (average 0.7 kg/m^3). Carbon content is variable between 20% and 48% to depths of between 0.3 m and to 0.6 m. The pH is around 4.03, with nitrogen contents around 0.89%. This group is found in climate region 2. Typical locations are King William Plains, Navarre Plains, Lake St. Clair and Clarence. The unsupervised soil cluster found under this group is 22.

Scrub

Coastal scrub on Holocene sands (S1)

This group was found on Holocene sands and sand dunes along parts of the west and south west coast of Tasmania. The group corresponds with TASVEG mapping unit SLW, floristic unit F2 and belongs to the broad vegetation class scrub. The group is found on Holocene sands close to swales where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year (see Plate 5.21). This results in a water table that is at or near the surface when rainfall is high, but lower during prolonged periods without precipitation. Often this group has a deep organic accumulation layer which is no longer in a swale, but maintains a higher water table through the low porosity of the compacted organic deposits. Carbon content is high at around 43% to a depth of up to 1.3 m, grading from fibric to hemic with depth. The average nitrogen content is around 1.46%. The soils are acidic, with a pH around 3.73, which aids the reducing conditions. This group is found in climate region 3. The unsupervised soil clusters found in this group are 3 and 13. Typical locations are Strahan and Trial Harbour.

Plate 5.21

S1 – scrub on Holocene sands. Ocean Beach, western Tasmania.

Riverine scrub on quartzite (S2)

This group was found on Precambrian quartzite and siliceous conglomerates on deep valleys or in depressions throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit SMM, floristic unit F2 and belongs to the broad vegetation class scrub. The group is found in depressions or the edge of depressions near rivers where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year (see Plate 5.22). Carbon content is around 24% to a depth of up to 1 m grading from fibric to sapric organic deposits with depth. The average nitrogen content is around 0.55%, and the pH of around 3.49, which aids the reducing conditions. This group is found in climate region 4. The unsupervised soil cluster found in this group is 12. Typical locations are along the South Coast Track, Anthony River Road and Lyell Highway.

Plate 5.22

S2 – riverine scrub in the Twelvetrees Range with scrub vegetation along drainage lines.

Scrub in waterlogged swales and depressions (S3)

This group was found in swales on Holocene sands and sand dunes along parts of the west and south west coast of Tasmania and in depressions on Precambrian quartzite and siliceous gravels throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit SMR and SMW, floristic units B13 and F1 and belongs to the broad vegetation class scrub. The group is found in depressions and swales where organic matter accumulation occurs through the maintenance of a high water table for a portion of the year (see Plate 5.23). The soils are therefore well humified, grading from hemic to sapric, although water table was measured at Strahan from 0.5 m above the surface to 0.75 m below the surface the latter in drought conditions. Carbon content is high at around 45% to a depth of up to 1.2 m. The average nitrogen content is around 1.23%, and the pH around 3.16, which aids the reducing conditions. This group is found in climate region 3. Typical locations are Strahan and Cox Bight. The unsupervised soil cluster found under this group is 17.

Plate 5.23

S3 – scrub in waterlogged swales. Ocean Beach, western Tasmania.

Scrub on slopes (S4)

This group was found on slopes on Precambrian quartzite and siliceous conglomerates throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit SSW, floristic units F1 and belongs to the broad vegetation class scrub. The group is found on well-drained slopes under scrub communities, or in fire and drought protected concave slopes, where drainage is good and reliable runoff provides a consistent water supply (see Plate 5.24). The soils are therefore fibric, grading to hemic with depth, with an average carbon content of around 43% to depths of around 1 m. The nitrogen content of the surface horizon is higher than the surrounding moorland at around 1.3%, grading to 0.84% with depth. The low pH around 3.29 aids in the accumulation of organic matter through reducing conditions. This group is found in climate region 5. Typical locations are Newton Creek and the Twelvetrees Range. The unsupervised soil cluster found under this group is 11.

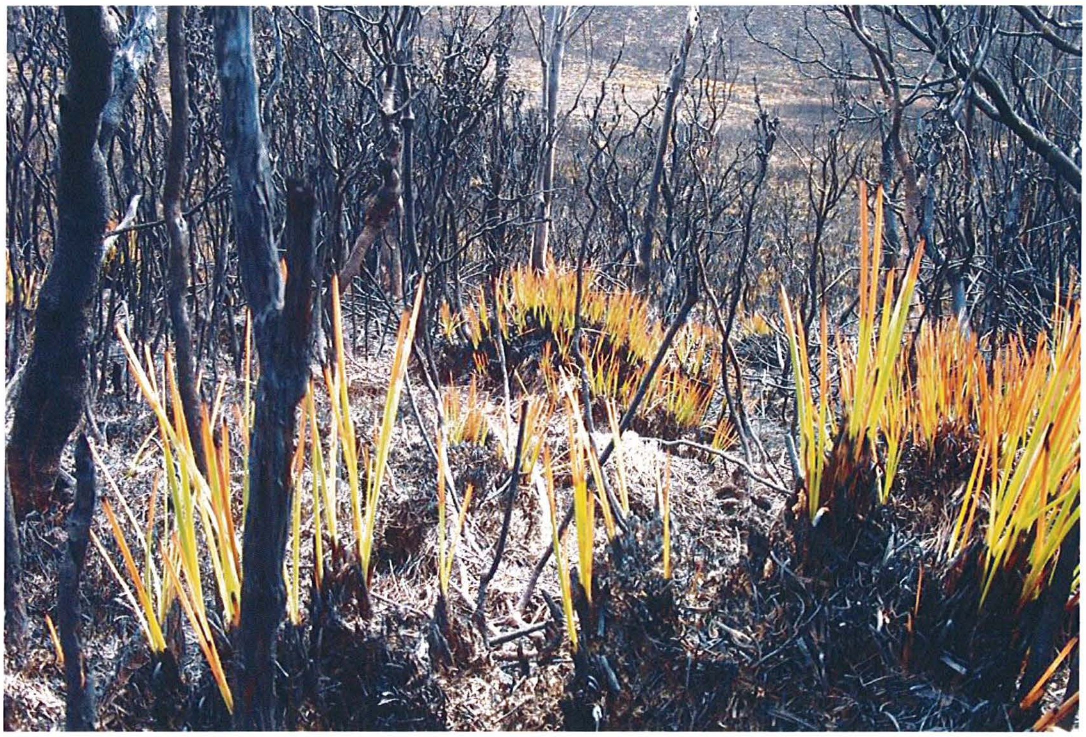

Plate 5.24

S4 – scrub on slopes. Twelvetrees Range, south west Tasmania.

Mound forming scrub (S5)

This group was found on Precambrian quartzite and silica-rich conglomerates in broad valleys and sandar throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping unit SWW, floristic unit F1 and belongs to the broad vegetation class scrub. Gravel rises on sandar provide islands for plant colonisation and good drainage allows for a rapid succession through from moorland to scrub communities (see Plate 5.25). The organic matter accumulation produces mounds of organic soils, raised above the level of the surrounding plains, resulting in a fibric upper horizon on top of more humified deposits, raised above water channels. The pH, at around 3 in the surface horizon and an average of 3.16 in the lower horizons, is the lowest of the scrub types found on nutrient-poor substrates. Fertility, with a nitrogen content of around 1.13% in the lower horizons and 1.57% in the surface horizons, is higher than the surrounding moorland. Organic soil depths are up to 2 m. This group is found in climate regions 3 and 4. Typical locations are Louisa Plains, Edgar Ponds, Red Point Hills and McPartlan Pass. The unsupervised soil clusters found under this group are 13 and 17.

Plate 5.25

SM – mound-forming scrub. Louisa Plains, south west Tasmania.

Wet Eucalypt forest

Eucalypt forest on sandstone or granite (F1)

This group was found on slopes on sandstone and granite in isolated outcrops in the west and south west of Tasmania. The group corresponds with TASVEG mapping unit WNL, floristic unit Nit0 and belongs to the broad vegetation class forest (see Plate 5.26). The soils are fibric, with an average carbon content of around 7% with a maximum organic carbon content of 12.5% to depths of up to 0.7 m. The nitrogen content of the surface horizon is around 0.79%, reflecting accumulation of nutrients or nitrogen-fixing organisms, grading to 0.23% with depth. The low pH of around 3.52 aids in the accumulation of organic matter through reducing conditions, although the lack of standing water table due to the porous nature of the underlying substrate results in oxidation of organic matter. This group is found in climate region 3. Typical locations are Granite Beach and South Cape Range. The unsupervised soil cluster found under this group is 5.

Plate 5.26

F1 – wet eucalypt forest on sandstone. Deadman's Bay, south west Tasmania.

Eucalypt forest on quartzite and sands (F2)

This group was found on slopes on Precambrian quartzite, siliceous conglomerates and Holocene sands throughout the west and south west of Tasmania. The group corresponds with TASVEG mapping units WNL, WNR and WOR, floristic units Nit0, Nit2 and OB1001 and belongs to the broad vegetation class forest (see Plate 5.27). The group is found where organic matter accumulation occurs on well-drained slopes or valley floors on the edge of buttongrass and scrub communities, or in fire and drought protected concave slopes, where drainage is good and reliable. Runoff provides a consistent water supply. The soils are therefore fibric, grading to hemic with depth with an average carbon content of around 24% to depths of around 1 m. The nitrogen content of the surface horizon is higher than the surrounding moorland at around 1%, grading to 0.43% with depth. The pH is approximately 3.49. This group is found in climate region 3. Typical locations are Spica Hills, Newton Creek and the Twelvetrees Range. The unsupervised soil clusters found under this group are 4, 5, 6, and 10.

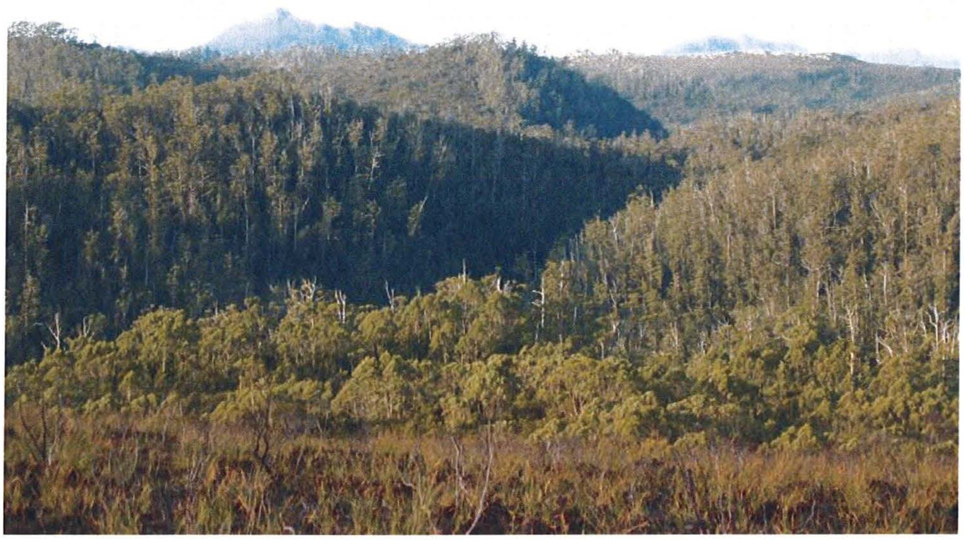

Plate 5.27

F2 – eucalypt forest on quartzite. Twelvetrees Range, south west Tasmania.

Leptospermum, Melaleuca forest

Non-eucalypt forest (N1)

This group was found on Precambrian quartzite, along the coast of west and south west Tasmania. The group corresponds with TASVEG mapping unit NLE, floristic unit D4d and Nit2 and belongs to the broad vegetation unit non-eucalypt forest (see Plate 5.28). Organic content is around 19% to depths of around 0.4 m. Organic accumulation occurs in locations where the water table remains high for part of the year, which is reflected in the humification of the lower horizons. Nitrogen levels in the lower horizons are approximately 0.19% with a pH of approximately 3.78. This group is found in climate region 3. A typical location is Louisa Bay. The unsupervised soil clusters found under this group are 12 and 18.

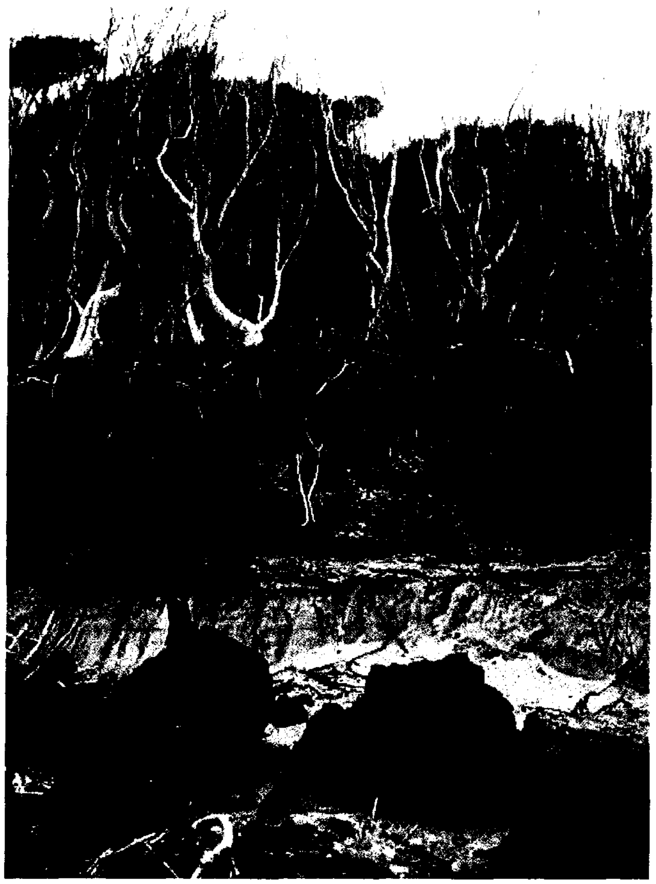

Plate 5.28

N1 – non-eucalypt forest. Ocean Beach, western Tasmania

Rainforest and related scrub

Coastal rainforest (R1)

This group was found on sands, sandstone and Precambrian metamorphic quartzite, along the coast of west and south west Tasmania. The group corresponds with TASVEG mapping unit RCO, floristic units C32, OBO1101 and F1 and belongs to the broad vegetation unit rainforest (see Plate 5.29). Organic content is around 24% to depths of around 0.5 m. Organic accumulation occurs with high rainfall in climate region 3 and/or the presence of a water table for part of the year. Nitrogen levels in the lower horizons are approximately 0.57%, with a pH of around 3.83. This group is found in climate region 3. Typical locations are Cox Bight and South Cape Rivulet. The unsupervised soil clusters found under this group are 2, 5 and 18.

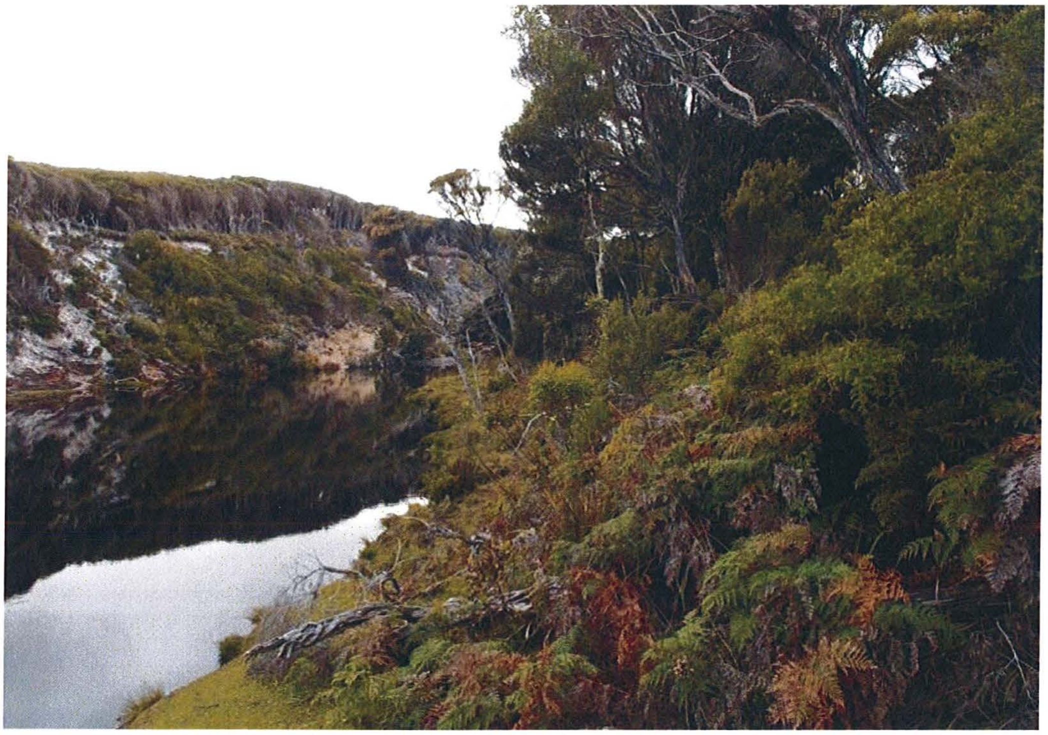

Plate 5.29

R1 - Coastal rainforest on Holocene sands. South west coast of Tasmania.

Callidendrous rainforest (R2)

This group was found in small patches on sands and Precambrian quartzite in west and south west Tasmania. The group corresponds with TASVEG mapping unit RMT, floristic units C1.1, T8.1 and T7.1 and belongs to the broad vegetation unit rainforest. Organic content is around 30% to depths of around 0.2 m. The pH is approximately 3.74. There is no permanent water table. Nitrogen in the upper horizon is approximately 1%, grading to 0.45% in the lower horizons. This group is found in climate region 3. Typical locations are Deadmans Bay and other fire-protected bays along the south west coast of Tasmania. The unsupervised soil cluster found under this group is 1.

Plate 5.30

R3 – thamnic rainforest on quartzitic glacial outwash at Louisa River, south west Tasmania.

Thamnic rainforest (R3)

This group was found on Precambrian quartzite on slopes in fire-protected locations in the west and south west Tasmania. The group corresponds with TASVEG mapping units RMS and RMT, floristic units T1.1, T3.1, T7.1 and T8.1 and belongs to the broad vegetation unit rainforest (see Plate 5.30). The group is characterised by highly organic, fibric deposits grading to hemic with depth. Organic content is around 45% to depths of around 1 m, with deposits of over 2 m of organic carbon content of 45% or more to bedrock measured in locations. The upper horizon has a pH of approximately 2.6 and a lower horizon pH of around 3.19. The upper horizon nitrogen content is 1.26%, grading to 0.87% in the lower horizons. This group is found in climate regions 3, 4 and 5. Typical locations are Newall Creek, Mount Murchison, Mount Sprent, Celery Top Islands and Port Davey Track. The unsupervised soil clusters found under this group are 1, 3, 4 and 13.

Implicate rainforest (R4)

This group was found on slopes, predominantly on glacial till derived from Precambrian quartzite and on sandstone or phyllite, in the west and south west Tasmania. The group corresponds with TASVEG mapping unit RKP and RMT, floristic units I1.1, M1.1 and COC00 and belongs to the broad vegetation unit rainforest (see Plate 5.31). Organic content is around 37% to depths of 0.8 m. The pH is approximately 3.91. Nitrogen in the upper horizon is 1.37%, grading to 1.10% in the lower horizons. This group is found in climate region 5. Typical locations are at Lake Margaret and Dove Lake. The unsupervised soil clusters found under this group are 2 and 3.

Plate 5.31

R4 –implicate rainforest rainforest on Owen conglomerate on Mt. Murchison, western Tasmania.

Mixed forest to rainforest on slopes (R5)

This group was found on slopes predominantly on Precambrian quartzite in the west and south west Tasmania. The group corresponds with TASVEG mapping unit RML and RMT, floristic unit Nit0 and belongs to the broad vegetation unit rainforest. These forests occur fire-protected slopes or shelves on slopes, sometimes grading to implicate or thamnic rainforest (see Plate 5.32). Organic content is around 38% to depths of around 0.4 m. The pH is approximately 2.9 in the surface horizon and 3.19 in the lower horizons. Nitrogen content in the upper horizon is 1.28%, grading to 1.08% in the lower horizons. This group is found in climate region 4. Typical locations are on the Ironbound Range and Tyndall Range. The unsupervised soil cluster found under this group is 10.

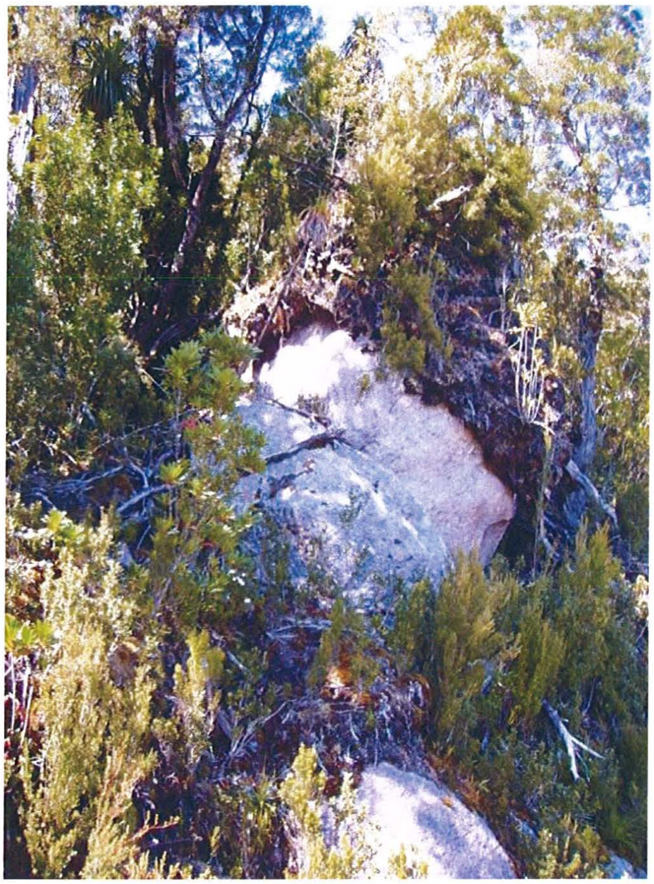

Plate 5.32

R5 –rainforest on slopes on Owen conglomerate on Mt. Murchison, western Tasmania.

Mixed forest to rainforest on gentle slopes (R6)

This group was found on slopes predominantly on Precambrian quartzite in the west and south west Tasmania. The group corresponds with TASVEG mapping unit RMT, floristic unit Nit0 and belongs to the broad vegetation unit rainforest. These forests occur fire-protected regions on gentle slopes or rises, often grading from eucalypt forest or scrub to implicate or thamnic rainforest (see Plate 5.33). Organic content is around 47% to depths of around 0.6 m. The pH is approximately 3.4 in the surface horizon and 3.54 in the lower horizons. Nitrogen content in the upper horizon is 1.04%, grading to 0.35% in the lower horizons. This group is found in climate region 3. Typical locations are on the Ironbound Range and Tyndall Range.

The unsupervised soil cluster found under this group is 11.

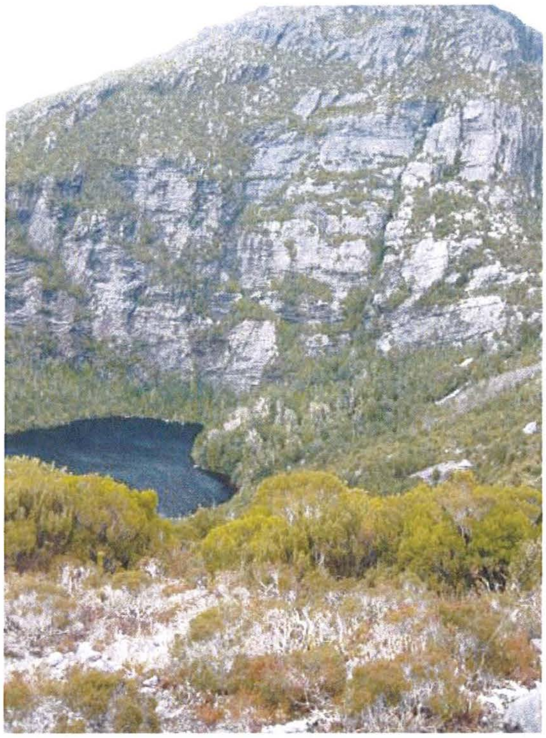

Plate 5.33

R6 –rainforest on slopes around a corrie on Owen conglomerate on Mt. Murchison, western Tasmania.

Rainforest in depressions (R7)

This group was found in valleys, predominantly on Precambrian quartzite, but with phyllites present, in the west and south west Tasmania. The group corresponds with TASVEG mapping unit RMT and floristic unit T1.1, and belongs to the broad vegetation unit rainforest. These rainforests occur in fire-protected regions in depressions and valleys where phyllites have been washed or eroded in, resulting in localised clays. The average soil organic carbon content is therefore low, at around 9%, although the range for organic carbon content can reach the lower limit for organosol. Nitrogen levels are low in the surface organic layer which forms a peaty or humose horizon of around 0.3 m with 0.69% nitrogen and a pH of around 3.65, sitting over a mineral soil. This group is found in climate region 3. Typical locations are along the South Coast Track and at Claytons. The unsupervised soil clusters found under this group are 7 and 9.

Eastern montane rainforest (R8)

This group was found on Jurassic dolerite in the Central Plateau. The group corresponds with TASVEG mapping unit RPP and floristic unit M5.1, and belongs to the broad vegetation unit rainforest. These rainforests occur in fire protected regions valleys and gentle slopes across the Central Plateau (see Plate 5.34). Organic content is around 40% to depths of around 0.3 m. Organic soil horizons grade to either clay or partially weathered glacial tills. Nitrogen content is high in the surface organic layer, with 2.02% nitrogen. The pH is around 3.49. This group is found in climate region 2. Typical locations are on the Central Plateau. The unsupervised soil clusters found under this group are 7 and 9.

Plate 5.34

R8 – eastern montane rainforest. Walls of Jerusalem, Central Plateau

Western montane rainforest (R9)

This group was found on Precambrian metamorphosed quartzitic sediments. The group corresponds with TASVEG mapping units RKP and RKF and floristic units I1.4, M1.1 and I2.1, and belongs to the broad vegetation unit rainforest. These rainforests occur in fire protected regions above around 700 m on western and south western mountain valleys (see Plate 5.35). Organic content is around 34% to depths of around 0.4 m. Nitrogen levels are high in the surface organic layer, with 0.99% nitrogen compared with 0.62% in the lower horizons. The pH is approximately 3.24. This group is found in climate region 5. Typical locations are on Mount Murchison and the Tyndall Range. The unsupervised soil clusters found under this group are 4 and 10.

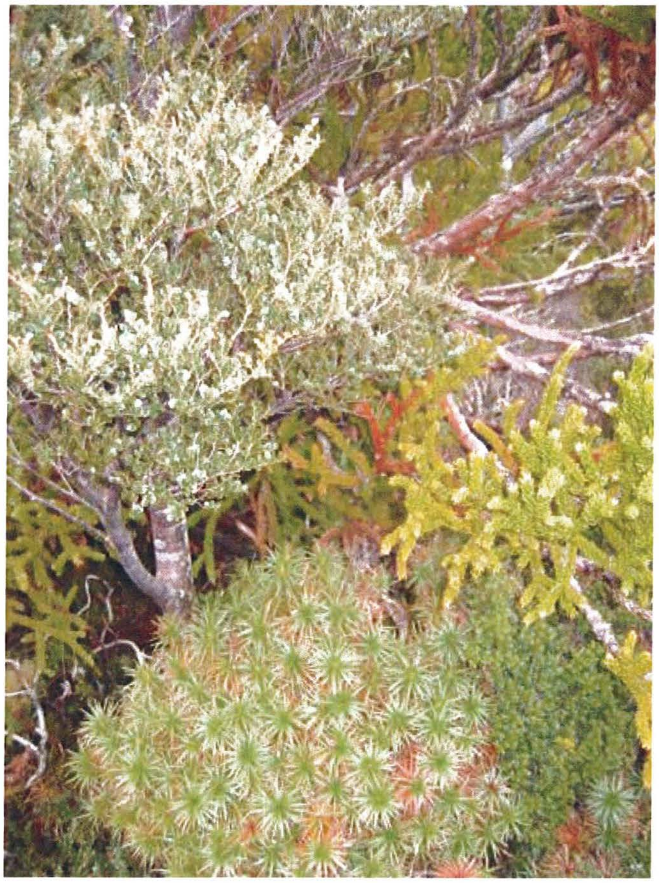

Plate 5.35

R9 – western montane rainforest. Tyndall Range, western Tasmania.

5.4 Discussion

The dominant soil-forming factors, recognised by Jenny (1941), of vegetation, geology, climate, topography and time, can be useful in predicting soil characteristics and soil groups produced through unsupervised clustering.

For soil classification and taxonomy purposes, a delineation of the soil group organosol using organic carbon content and depth has been used. The Australian system (Isbell 2002) has been taken directly from the U.S. soil classification system (Soil Survey Staff 2005) and applied to organic soils here, without the soils being fully described first, in other words, a top-down approach has been used. This has failed to adequately account for processes, a function of soil taxonomy which has been deemed essential in the Australian soil classification system (Isbell 2002). While the unsupervised clustering groups the organic soil types, a supervised clustering, using the dominant environmental variables and the dominant soil forming variables found in the literature, provides the link between soil characteristics and soil-forming factors.

The current suggested division of organosols into fibric, hemic and sapric fails to adequately describe the processes dominant in organic soil formation in Tasmania. Fibric soil (soils with low humification) are found under waterlogged, minerotrophic, higher nutrient conditions, in topographic depressions with *Sphagnum* and Cyperaceous species forming the organic materials, while fibric soils, with low humification are also found, but under well-drained, nutrient poor geology, on a range of topographic positions from steep slopes and valleys with rainforest species forming the organic materials.

On nutrient poor sites on oligotrophic rocks, the effect of waterlogging is to produce predominantly sapric organic soils under Restionaceae and Cyperaceae species, which often grade to sapric through fibric and hemic upper horizons. An exception to this is where waterlogging is a result of flushing from river channel overflow, which then produces either sapric or sapric deposits with a thin fibric horizon, the fibric horizon is predominantly composed of bryophytes and Restionaceae roots. Fibrous soils are found in areas of good drainage and/or areas with longer fire free intervals that are undergoing succession from buttongrass moorland through to scrub with emergent Myrtaceae species.

Soil classification should be based on measurable, observable and relatively stable soil characteristics (Isbell 2002), rather than a presumed genesis. A broad division in to fibric, hemic and sapric does not adequately classify the Tasmanian organosols with further differentiae and classes required. In order to assess the current state of organosols and the conditions under which they occur, the differentiae of soil organic carbon content and depth which classifies organosols needs to be used to model and map the extent of organic soil (Isbell 2002). This is important as the current soil organic carbon content and organic soil depth values have been taken from other nations' soil taxonomies, based on what was found in their geographic regions rather than what is found in Australia. As can be seen in the overview of the parameters that constitute an organosol in Chapter 2, the soil organic carbon content and organic material depth values differ between the taxonomies. There is therefore the danger that a large proportion of Tasmanian soils may not come under the class organosol due to these limits or may need to be re-classified under tenosols. It has also been stated in the Australian Soil Classification that a classification should be accompanied by means of soil surveying and mapping, which requires a geographical prediction of the occurrence of organosols through predictable soil forming factors. Through the use of the dominant organic soil forming factors found in this chapter, model building and mapping of the geographic conditions and extent of organosols is undertaken in Chapter 6. The models should therefore affirm the robustness of the use of vegetation and geology as suggested differentiae in the classification of organosols and also tenosols, as suggested by Isbell *et al.* (1997) and Isbell (1996, 2002).

Chapter 6

Modelling and accounting of soil organic stocks in Tasmanian organosols

6.1 Introduction

The purpose of this chapter is to model soil organic carbon stocks within the soil order organosol for Tasmania, with a view to integrating the results in a proposed classification for organosols in Chapter 7.

Classification through unsupervised clustering techniques has produced divisions in the soil order organosol, describable in terms of organic carbon content, humification, total nitrogen content and depth of the organic layers. In Chapter 3, the soils were described in terms of organic carbon content, humification, total nitrogen content and depth of the organic horizons and these in turn were predictable in terms of the dominant soil forming factors. It is desirable that any general classification for these soils reflects the differences highlighted through both the supervised and unsupervised clustering. A classification might also desirably reflect variation in the amount of soil organic carbon. As organic soils are, by definition, an accumulation of organic matter, it would be a useful and informative addition to a classification if sub-groups reflecting variation in organic carbon stocks were included. Soils can act as sinks or sources for atmospheric carbon (Cannell and Milne 2000, Eswaran *et al.* 1995) with soil organic carbon pools possibly more than three times that of the above-ground terrestrial biomass carbon pool (Eswaran *et al.* 1993). Organic carbon content in soils has already been measured and typified in certain regions after calls for more accurate soil organic carbon stock estimates at the 1992 Rio Summit (United Nations 1993) and the subsequent requirement for signatory countries to produce baseline data on soil organic carbon stocks under the Kyoto Protocol to the United Nations Framework Convention on Climate Change. European estimates have been produced for use with the European Soil Database at a 1 km x 1 km resolution (Jones *et al.* 2005) to a depth of 30 cm for mineral soils and to greater depths for many organic soils. Brazilian soil carbon stocks have also been estimated to a depth of 30 cm (Bernoux *et al.* 2002). Organic carbon soil stocks have also been estimated to depths of 2 m (Batjes 1996, Mikhailova and Post 2006), 3 m (Jobbágy and Jackson 2000) and to total depth (DEFRA 1998). As organic soil is predominantly an accumulation of the vegetation biomass, it would be expected that bulk densities and organic content would differ between vegetation types. It is expected that a model for predicting soil organic carbon could be produced for Tasmania in terms of the dominant soil forming factors. Vegetation type, land use and climate were used to estimate soil organic carbon in European soils due to the effects of these factors on both bulk density and organic carbon content of the soil (Jones *et al.* 2005). Other groupings of soil organic carbon content values have been through separating soils into biomes (Jobbágy and Jackson 2000) and regionally into vegetation mapping units (Bernoux *et al.* 2002). Organic soils are defined according to organic carbon content with classifications of organic soils including divisions that relate to dominant vegetation composition of the accumulating organic material, depth of the organic materials, humification of organic materials and soil temperature (Soil Classification Working Group 1998, FAO 2000, Isbell 2002, Nyborg and Solbakken 2003, FAO 2006, Soil Survey Staff 2006).

Even though organic soils are defined in terms of soil organic carbon content and depth, there has been no attempt to test whether the organic content and depth values chosen for the Australian Soil Classification (Isbell 2002) adequately capture the nature and greatest areal extent of Tasmanian organic soils. The aim of this chapter is therefore to provide a geographic context for the organic soil classifications developed in Chapters 3 and 5 and to produce a model or set of models of organic soil carbon content in the organic soils of Tasmania which can predict the geographic settings under which organic soils and organic soil accumulation occur. The models will then provide the output to enable mapping of the areal extent of organic soils and provide an estimation of soil organic carbon.

6.2 Methods

6.2.1 Soil and environmental variables

Site selection, site characteristics, soil variables and environmental variables are described in chapters 3 and 4. The complete set of both soil and environmental variables was used for data analysis with the additional variables of carbon volume, radiation index and slope. Carbon volume was calculated using the soil variables percent organic carbon, bulk density and depth of the organic horizons, using the following equation (Schwager and Mikhailova 2002):

$$SOC = C \times \rho \times d$$

where *SOC* (soil organic carbon) is the mass of soil organic carbon per unit area in kg per m^2, d is the total depth of the organosol in metres, ρ is the bulk density of the soil in kg per m^2 and C is the percent soil organic carbon in the sieved proportion of the soil $\leq$ 2 mm. Inorganic carbon was excluded. Dissolved organic carbon and dissolved inorganic carbon were not included in the soil organic carbon value.

Slope, in degrees, was measured at each site and was used to calculate topography as described in Chapter 4. Although the environmental variable topography, was assigned a 7 point ordinal scale, the full range of the scale did not appear in each vegetation grouping shown in Table 6.1. It was therefore decided to use the variable slope instead. The methods for determining bulk density, depth and percent organic carbon are discussed in Chapter 3.

6.2.2 Data analysis

The data set used for this chapter includes those soil pits found to be classified under organosol, as well as those sites that were too shallow to satisfy classification as an organosol and therefore fell under the definition of a tenosol with a humose or peaty horizon according to the Australian Soil Classification System (Isbell 2002).

All statistical analysis was performed using R 2.2.1. A Kruskal-Wallis rank sum test was performed on both the supervised and unsupervised clustering for variance in carbon volume values between the groups, followed by pairwise t tests on the individual clusters, using R 2.2.1. From the results of the Kruskal-Wallis rank sum test and pairwise t tests, it was clear that, while the supervised and unsupervised clustering could adequately describe and distinguish mean carbon volume between certain clusters, the range of carbon volume within the individual clusters was large. It was therefore decided to test for factors and variables that might be influencing the carbon volumes found in organosols. Pairwise plots of carbon volume and the environmental variables revealed clusters in the data and therefore divisions in the data set were necessary. The divisions fell into broad vegetation groups with further divisions necessary according to geology, altitude and proximity to the coast. Final groupings are shown in Table 6.1 with codes used in the plots in the results section.

Table 6.1

Vegetation divisions apparent in pairwise plotting of the environmental variables with carbon volume as the predictor. The vegetation groups are a subset of the vegetation groups found through supervised clustering in Chapter 5. The codes have been assigned to aid plotting legibility. TASVEG mapping units are from Harris and Kitchener (2005), floristic units are from Kirkpatrick *et al.* (1995), unsupervised cluster groups are from Chapter 3 and supervised cluster units are from Chapter 5.

Codes used in this chapter	*broad vegetation groups*	*TASVEG*	*floristic units*	*unsupervised*	*supervised*
a	alpine on nutrient-poor geology	HSW HCM	A24 A28 A30 A31 A32 A35	6 10 11 12	A8 A9
a3	alpine on nutrient-rich geology	MSP HSE HUE HCM	A3 A8 A16 S2 S3 S4	14 15 16 17 20 21	A1-A7
m	moorland on nutrient-poor geology	MBR MBW MRR MBP MBS MSW	B1a B1b B2 B3 B4 B5 B15	5 6 7 8 9 18 22 23	B1-B8 BR1 BR2
m3	moorland on nutrient-rich geology	MBE MGH MBU MBP	A8 E7 E8 B1a B2	7 9 12 21	BC1-BC3
mc	low altitude moorland close to coast	MBR MBW MSW MBS	B1a B1b B2 B4 B5	5 6 7 8 9 16 17 18 19 22	B1-B8 BR1-BR2

Codes used in this chapter	*broad vegetation groups*	*TASVEG*	*floristic units*	*unsupervised*	*supervised*
		MRR			
s	Scrub	MBS MBW SWW SLW SMR SMM SSW	B2 B4 F1 F2	11 12 13 17 22	BM S1-S5
f	Forest	WNR RMT SWW RML WNL	F1 NIT0	3 10 11 13	F2 R5 R6 S5
cf	forest close to coast	WOR WNL WNR	OBO111 OB1001 NIT0 NIT2 D4d	2 5 10	R1 F2 N1
rf	Rainforest	RMT RMS	I1.1 T1.1 T3.1 T8.1 C1.1	1 3 4 10 13	R2 R3 R4
crf	rainforest close to coast	RCO NLE	OB0111 F1 NIT2 C32	1 2 5 12 18	R1
mrf	montane rainforest	RKP RKF RPP	I2.1 I1.4 M1.1 M5.1	2 4 16	R4 R8 R9

Regression analysis was performed on the complete data set using the MASS package in R 2.2.1. Linear modelling was used where possible to ease application for future use in GIS software and interpretability by land managers. A stepwise linear modelling procedure was used initially using the MASS package (Venables and Ripley 2005) in R 2.2.1, followed by diagnostics using both visualisation methods and normality tests for possible transformations. Regression assumptions of constant variance, normality and correlated errors were checked and diagnostics were also performed to consider the effects of outliers, leverage, influential observations and structure of the relationship between predictors and response variables with outputs of the diagnostics provided in Appendix 13. Both visualisation methods and Box-cox transformations were used to ascertain transformations of the variables using the MASS package in R 2.2.1 (Box and Cox 1964, Venables and Ripley 2002, Faraway 2005). Where non-linear models were necessary, a generalised additive model (Wood and Augustin 2002) was used employing the mgcv package (Wood

2006) in R 2.2.1. The generalised additive model used in the mgcv package constructs functions and one or more quadratic penalty coefficient matrices for each smooth term in the model formula, creating a model matrix for the strictly parametric part of the model formula, and combines these to obtain a complete model or design matrix and a set of penalty matrices for the smooth terms. Penalised iteratively reweighted least squares are used (Wood 2000) and, at each iteration, a penalised weighted least squares problem is solved using the smoothing parameters estimated by GCV. Eventually both model parameter estimates and smoothing parameter estimates converge. While a generalised additive model may provide a better fit, the output is more difficult to interpret for land managers and more problematic to apply in GIS, therefore a linear model was produced in each case, and an ANOVA used to compare the performance of the linear and the generalised additive model.

Although the linear models produced for each vegetation group shown in Table 6.1 are intended as a training set, against which additional sites can be tested, tables showing the range and mean of environmental variables and carbon volume (metric) for each vegetation grouping were produced. It is intended that the models will form part of a mapping project which will aim to calculate and therefore estimate carbon volumes in organosols in Tasmania.

6.2.3 Soil organic carbon calculations

In order to calculate the extent of organic soils in Tasmania and the estimate the amount of soil organic carbon contained within in the organic soils, it was necessary to use digital mapping tools and the digital data available to the author. Predictive mapping was carried out as follows.

1. Low nutrient geology and alluvial materials were extracted from the Geoscience Australia 1:250000 geology layer.

2. The vegetation types in Table 6.1 were extracted from the Land Information Systems Tasmania TASVEG layer and amalgamated into the groups in Table 6.2.

3. Average maximum temperatures were derived from spatial data provided by the Australian Bureau of Meteorology.

4. A buffer 300 m inland from the 1:250000 coastline was produced, which defined the coastal vegetation types.

5. The vegetation types were then split according to fertility groups based on geology and/or distance from the coast.

6. The derived linear relationships (Table 6.3) were used to estimate SOC content for each vegetation class (the upper values of the modelled outputs were restricted to the known upper values shown in Table 6.4).

7. All layers were combined to produce the final map.

6.3 Results

6.3.1 Soil organic carbon model

Soil organic carbon is best described using the supervised clusters, derived in Chapter 5. Difference in organic soil carbon was significantly discernible between the unsupervised clustering technique, floristic mapping units and TASVEG mapping units, but the supervised clusters performed better than all of these (Table 6.2).

Table 6.2

Kruskal-Wallis rank sum tests, significance values and degrees of freedom for classifications and soil organic carbon content (kg C m^{-2}). Unsupervised = unsupervised clusters produced in Chapter 4, supervised = supervised clusters produced in Chapter 5, floristic units = floristic units of vegetation described in Chapter 5 derived from Kirkpatrick *et al.* (1995), TASVEG broad mapping units = TASVEG broad mapping units of vegetation described in Chapter 5 derived from Harris and Kitchener (2005), TASVEG mapping units = TASVEG mapping units of vegetation described in Chapter 5 derived from Harris and Kitchener (2005), supervised broad vegetation units = broad vegetation units derived from the supervised clustering in Chapter 5. Boxplots of soil organic carbon for each classification are provided in Appendix 14.

Classifications	*Kruskal-Wallis Rank sum test*	*p value*	*df*
Unsupervised	636.59	$< 2.2 \times 10^{-16}$	22
Supervised	713.62	$< 2.2 \times 10^{-16}$	39
floristic units	581.70	$< 2.2 \times 10^{-16}$	41
TASVEG mapping units	520.20	$< 2.2 \times 10^{-16}$	29
TASVEG broad mapping units	348.84	$< 2.2 \times 10^{-16}$	10
supervised broad vegetation units	162.94	$< 2.2 \times 10^{-16}$	5

When considering the trends within the broad vegetation groups in the supervised clustering plot, there appear to be trends in the soil organic carbon content which roughly relate to the topographic divisions based on slope and topographic position in the supervised clustering. The plot of soil organic carbon on slope shows a weak, negative correlation with an R^2 of 0.24 (Figure 6.2) and divisions of the entire data set into broad vegetation classes produced in the supervised clustering were necessary to enable soil organic carbon modelling (Table 6.2).

Table 6.3

Linear and generalised additive model (GAM) R^2 and significance values for broad vegetation types for log soil organic carbon in kg C m^{-2}. Linear and GAM equations, standard errors, t and F values, degrees of freedom and diagnostics plots are provided in Appendix 13.

	predictors	R^2	*significance*	*GAM* R^2	*significance*
Alpine	slope	0.70	1.67×10^{-12}		
Alpine on dolerite	slope	0.83	$< 2 \times 10^{-16}$	0.88	$< 2 \times 10^{-16}$
Moorland coastal	slope	0.82	$< 2 \times 10^{-16}$	0.95	$< 2 \times 10^{-16}$
Moorland	slope	0.84	$< 2 \times 10^{-16}$	0.95	$< 2 \times 10^{-16}$
Moorland on dolerite	slope	0.86	$< 2 \times 10^{-16}$		
Scrub	slope	0.82	$< 2 \times 10^{-16}$		
Forest	slope, TAP	0.85	$< 2 \times 10^{-16}$		
Coastal forest	slope	0.92	$< 2 \times 10^{-16}$		
Montane rainforest	Ave Max Temp	0.81	$< 2 \times 10^{-16}$		
Coastal rainforest	TARD	0.77	3.39×10^{-10}		
Coastal rainforest	slope	0.72	4.53×10^{-9}		
Rainforest	slope, height, TARD	0.84	$< 2.2 \times 10^{-16}$		

Stepwise regression results consistently show slope as the dominant predictor in all the broad, supervised vegetation types, apart from montane rainforest (Table 6.3 and Figure 6.2). In all cases, apart from under rainforest and montane rainforest, as slope increases, within a specific broad vegetation type, soil organic carbon decreases (Figure 6.2). Linear modelling was used where possible, although generalised linear models produced a better fit in some cases. The log transformation of the predictor is to be expected, as an increase in 1 m in depth of the soil under 1 m squared would have a multiplicative effect on total soil organic carbon within that soil column. The results for each vegetation class are considered individually. The R^2 results for each predictor are provided in Table 6.4 with the range of predictor values for each vegetation class given in Table 6.5.

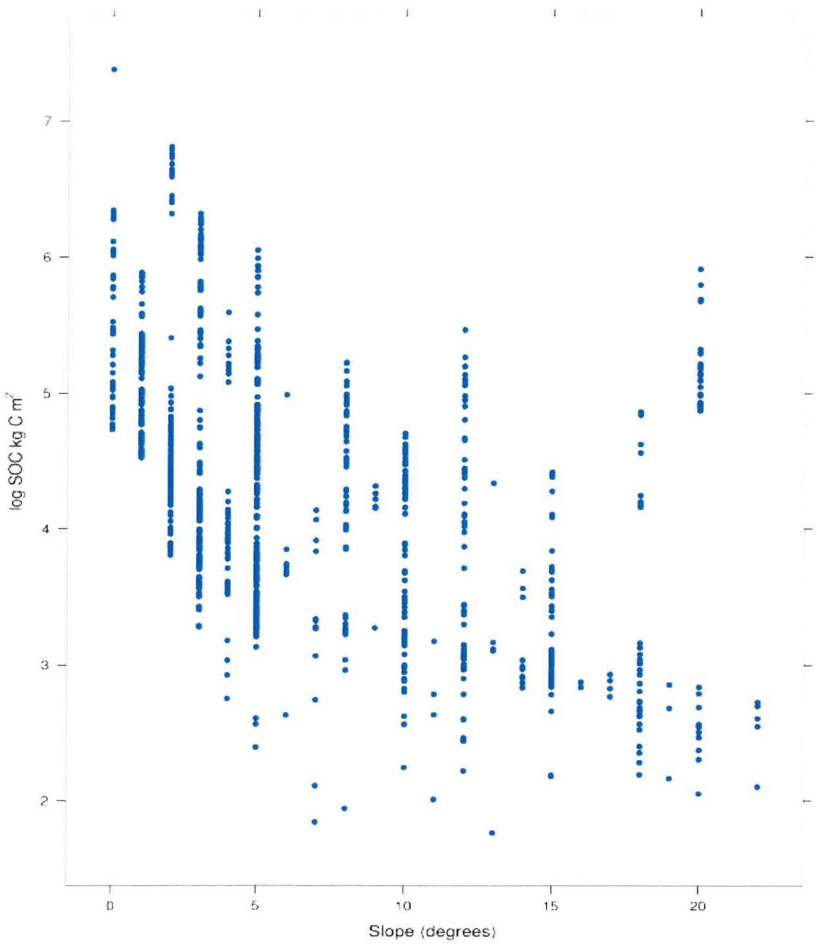

Figure 6.1

Correlation between slope angle in degrees for all sites and the log soil organic carbon storage in kg per m^2 to total organic soil depth. $R^2 = 0.24$, n = 1159.

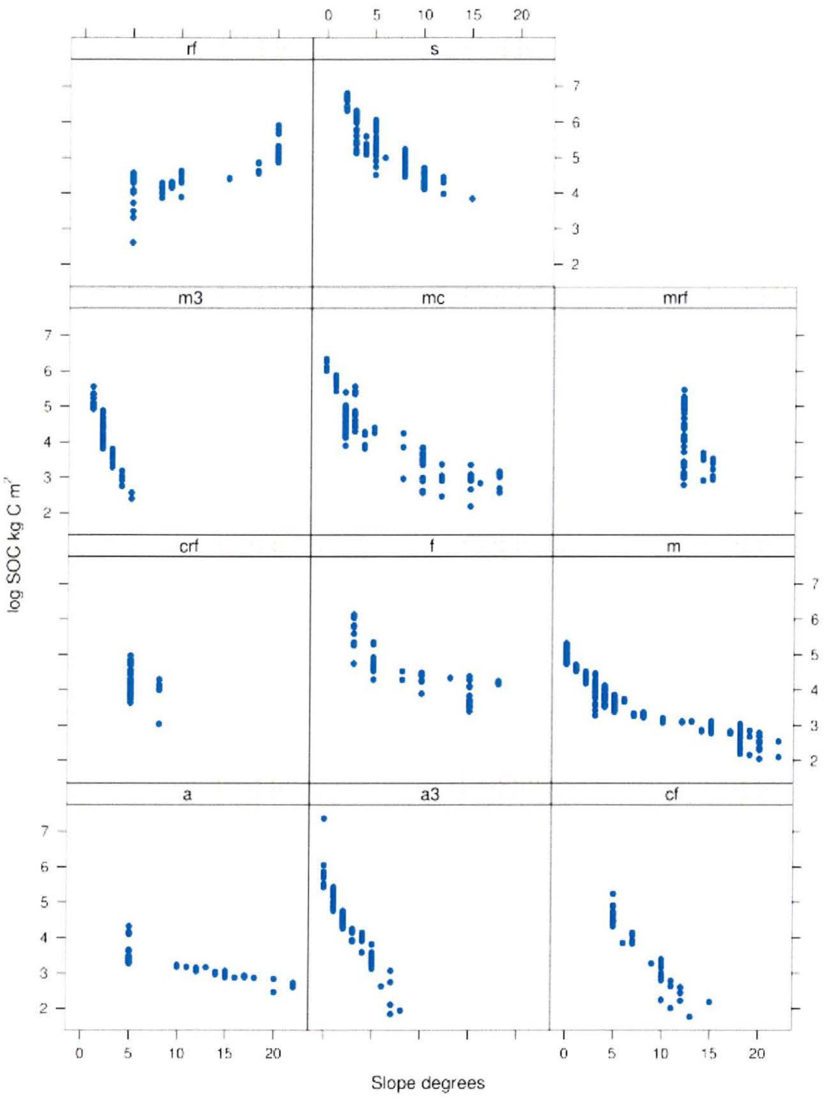

Figure 6.2

Correlations for individual vegetation types as defined in Table 6.1, with slope in degrees against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4

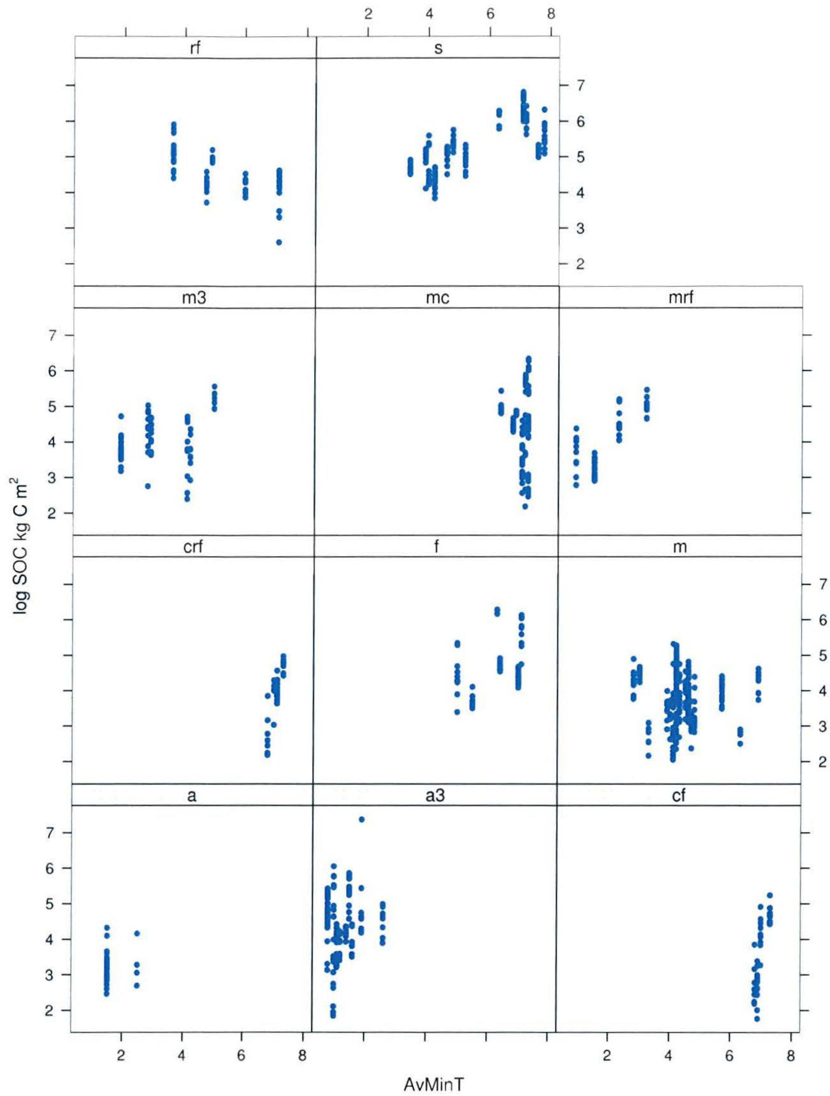

Figure 6.3

Correlations for individual vegetation types as defined in Table 6.1, with average daily minimum temperature in ° C against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4.

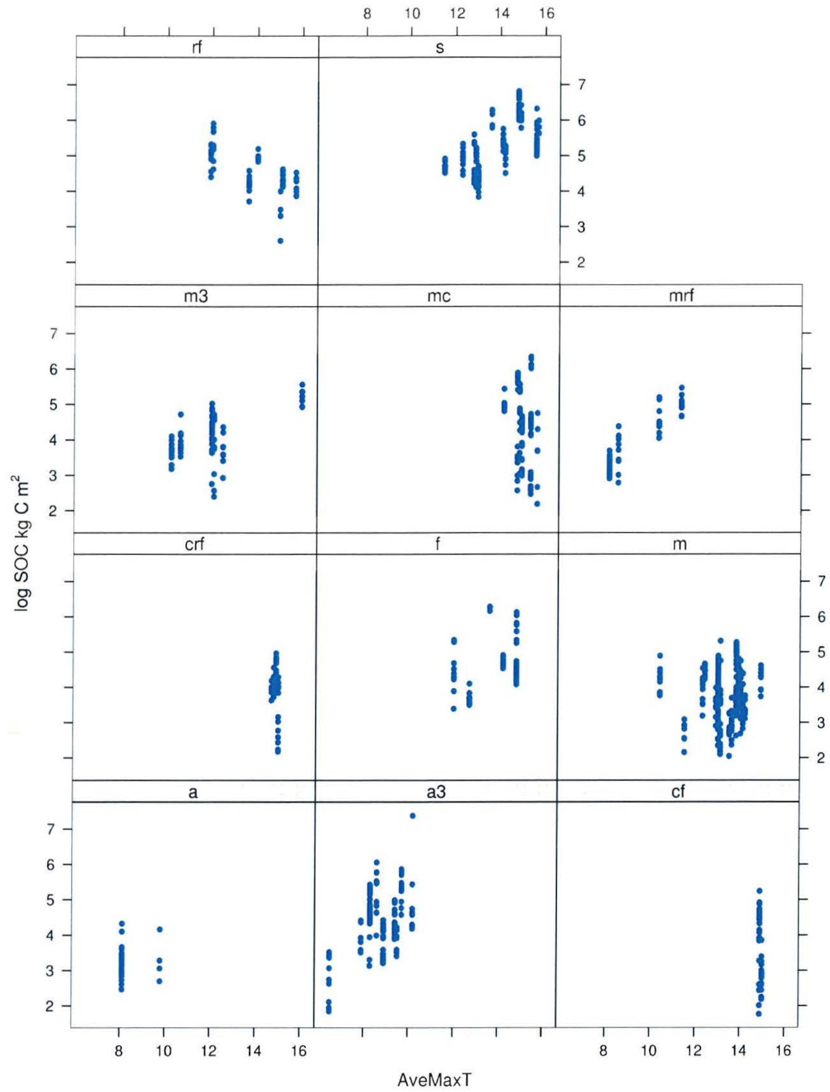

Figure 6.4

Correlations for individual vegetation types as defined in Table 6.1, with average daily maximum temperature during the driest quarter of the year in ° C against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4.

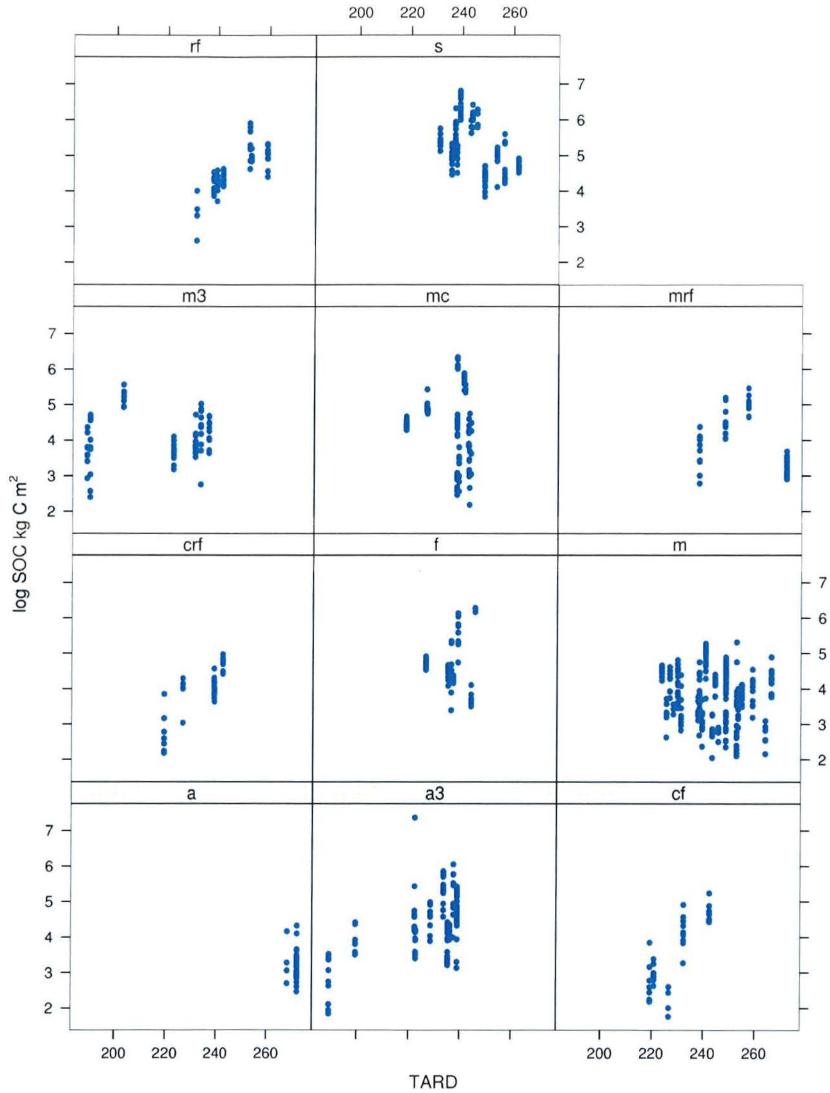

Figure 6.5

Correlations for individual vegetation types as defined in Table 6.1, with total number of rain days per annum against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4.

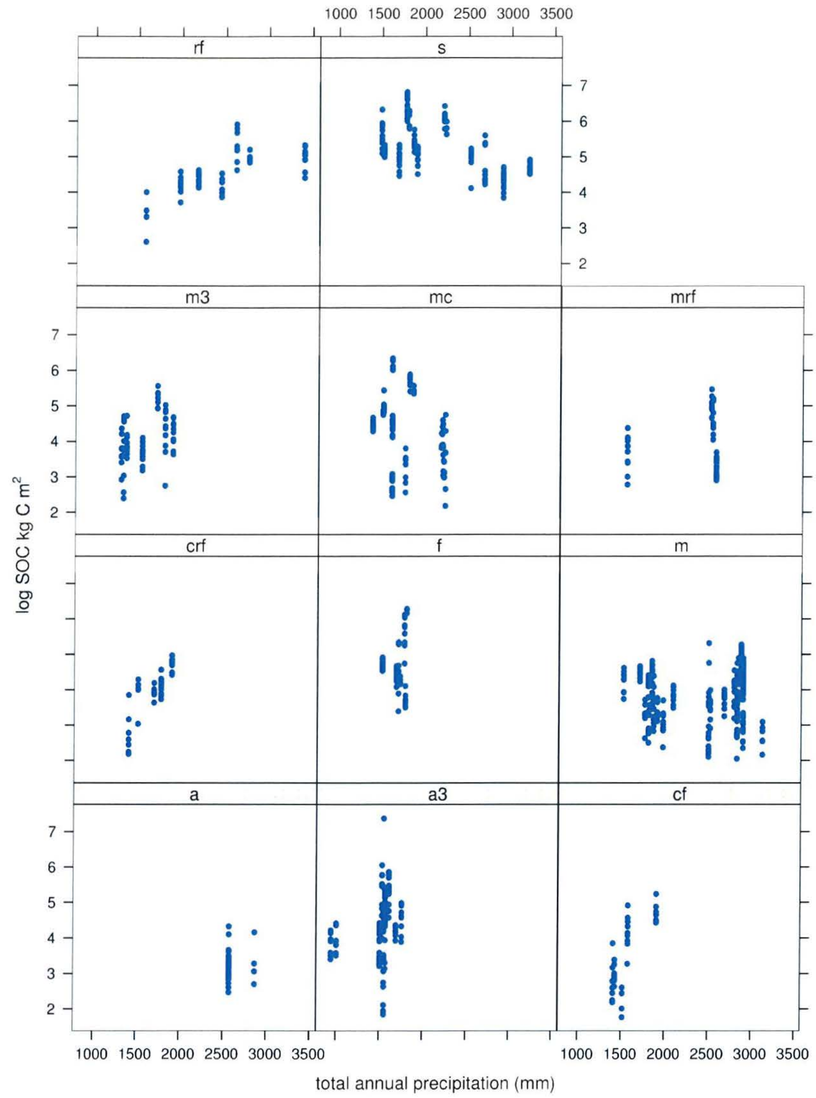

Figure 6.6

Correlations for individual vegetation types as defined in Table 6.1, with total precipitation per annum against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4.

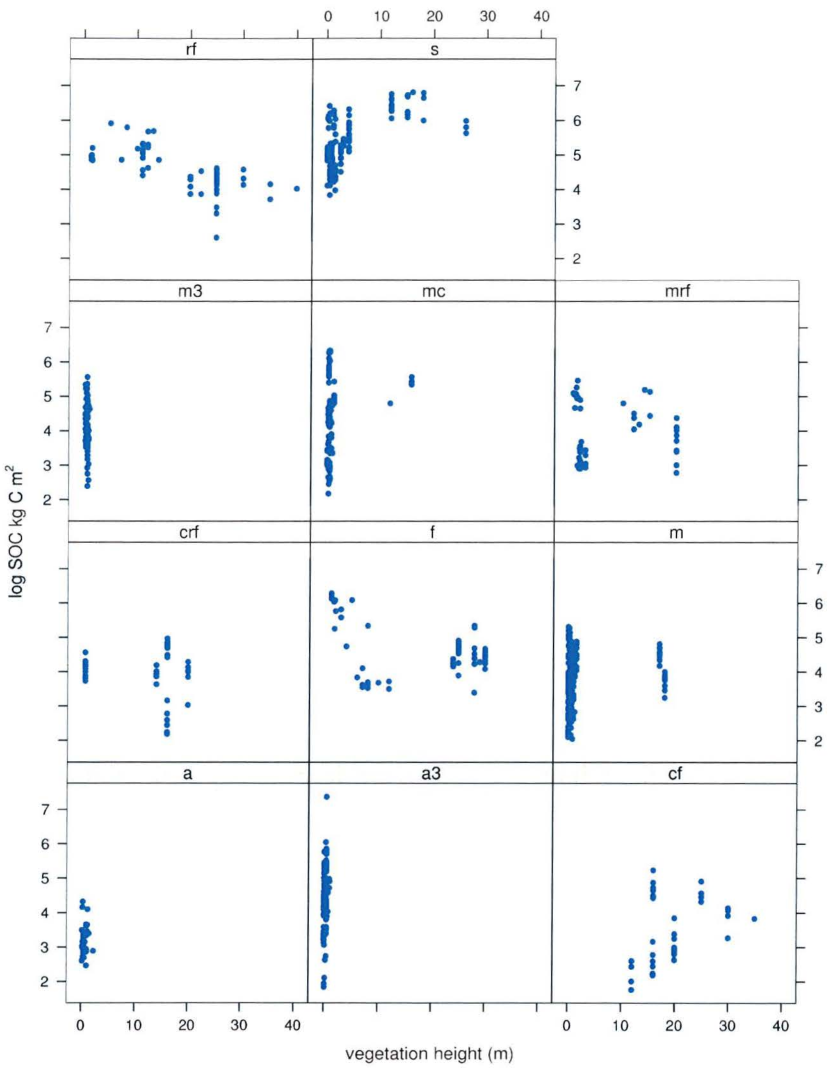

Figure 6.7

Correlations for individual vegetation types as defined in Table 6.1, with vegetation height of the tallest strata in metres against log of soil organic carbon in kg of organic carbon under one m^2 to total depth of organic soil. Individual R^2 are given in Table 6.4.

Table 6.4

R^2 values for the predictors presented in Figures 6.2 to 6.7. Codes for the predictors are explained in Chapter 4. Slope = slope in °, TAP = total annual precipitation (mm), TARD = total annual rain days, AveMinT = average daily minimum temperature, AveMaxT = average daily maximum temperature, Height = vegetation height. Codes for the vegetation types are explained in the methods section of this chapter.

Vegetation type	*Slope*	*TAP*	*TARD*	*AveMinT*	*AveMaxT*	*Height*
Rf	0.83	0.69	0.81	-0.70	-0.67	-0.69
S	-0.86	-0.51	-0.42	0.48	0.30	0.28
m3	-0.93	0.37	0.01	0.31	0.55	-0.08
Mc	-0.91	-0.23	-0.19	-0.13	-0.24	0.23
Mrf	-0.47	0.11	-0.41	0.77	0.90	0.05
Crf	-0.85	0.86	0.88	0.89	-0.60	-0.17
F	-0.73	0.60	0.48	0.23	0.09	-0.10
M	-0.92	0.09	-0.13	-0.02	-0.01	0.10
A	-0.84	0.10	0.10	0.10	0.10	0.00
a3	-0.91	0.31	0.58	-0.04	0.32	0.28
Cf	-0.96	0.77	0.82	0.80	-0.67	0.27

Table 6.5

Range of values for soil organic carbon stocks (SOC) under broad vegetation types and associated environmental conditions used as predictors; slope (°), total annual rain days, average daily maximum and minimum temperature in °C.

Broad vegetation types	*n*	*SOC kg C m^2*	*Slope°*	*Total annual precipitation (mm)*	*Total annual rain days*	*AveMaxT °C*	*AveMinT °C*
a	43	12-76	5-22	2576-2871	268-272	8.1-9.8	1.5-2.5
a3	166	6-1597	0-8	934-1760	189-239	6.5-10.2	0.8-2.6
m	304	8-204	0-22	1519-3125	223-266	10.4-14.9	2.8-6.9
m3	69	11-261	0-5	1302-1908	189-237	10.2-16	1.9-5
mc	117	9-569	0-18	1400-2242	218-244	14.2-15.7	6.4-7.3

Broad vegetation types	*n*	*SOC kg C m^{-2}*	*Slope°*	*Total annual precipitation (mm)*	*Total annual rain days*	*AveMaxT °C*	*AveMinT °C*
s	136	47-908	2-15	1492-3204	231-262	11.5-15.7	3.4-7.8
f	102	30-538	3-18	1526-1806	227-246	12-14.8	5-7.1
cf	62	6-190	5-15	1409-1908	219-243	14.9-15	6.8-7.3
rf	72	14-370	5-20	1580-3404	231-259	11.9-15.7	3.6-7.1
crf	38	9-145	5-15	1409-1908	219-243	14.7-15	6.8-7.3
mrf	50	16-237	12-15	1546-2576	238-272	8.1-11.3	0.9-3.2

Alpine on nutrient-poor geology

Organic carbon stocks under alpine vegetation on quartzite range between 12 and 76 kg m^{-2}. Carbon stocks are generally lower than in soils found under alpine vegetation on dolerite, but are found on steeper slopes, with organic soils accumulating on slopes of up to 25°. A linear relationship was found between slope and organic soil carbon with a decrease in total organic soil carbon with increase in slope angle.

Alpine on nutrient-rich geology

Organic carbon stocks under alpine vegetation on dolerite range between 6 and 1597 kg m^{-2}. The trend in soil organic carbon stocks under alpine vegetation on dolerite follows a topographic and wetness gradient with the lowest soil organic carbon found under heath and sedgeland on slopes and the highest soil organic carbon found in depressions, springs and drainage lines with a consistent water availability. The slope of negative correlation of soil organic carbon content with increased slope angle is steep, with the amount of carbon held in soil on slopes of 12° only 0.4% that found in topographic depressions and flats.

Coastal buttongrass moorland

Organic carbon stocks under coastal buttongrass moorland range between 9 and 569 kg $m^{-2.}$ Soil organic carbon also follows a linear or curvilinear trend with organic carbon stocks decreasing with an increase in slope. The lowest values of soil organic carbon are found on slopes of approximately 18° trending to the highest values of soil organic carbon on flats and depressions.

Buttongrass moorland on quartzite

Organic carbon stocks under inland buttongrass moorland range between 8 and 204 kg $m^{-2.}$ The highest values in soil organic carbon is less than half that of coastal buttongrass moorland, but the lowest values of soil organic carbon is found on slopes of 25°. Soil organic carbon also follows a linear and curvilinear trend with a decrease in soil organic carbon with an increase in slope.

Buttongrass moorland on dolerite

Organic carbon stocks under buttongrass moorland on dolerite range between 11 and 261 kg $m^{-2.}$ The trend in soil organic carbon follows a topographic trend where soil organic carbon stocks are greater in depressions and valleys, dropping sharply with increased slope angle. The lowest values of soil organic carbon are found on slopes of only 5°.

Scrub

Organic carbon stocks under scrub range between 47 and 908 kg $m^{-2,}$ with lowest values of soil organic carbon found on slopes of 15°. Soil organic carbon content also exhibits a negative, linear relationship with slope with a decrease in soil organic carbon stock with increasing incline.

Wet eucalypt forest

Organic carbon stocks under wet eucalypt forest range between 30 and 260 kg $m^{-2.}$ The lowest values of soil organic carbon are found on slopes of 18 °. Soil organic carbon content also exhibits a negative, linear relationship with slope with a decrease in soil organic carbon stock with increasing incline.

Coastal forest

Organic carbon stocks under coastal forest range between 6 and 190 kg $m^{-2.}$ The lowest values of soil organic carbon are found on slopes of 18 °. Soil organic carbon content also exhibits a negative, linear relationship with slope with a decrease in soil organic carbon stock with increasing incline.

Coastal rainforest

Organic carbon stocks under coastal rainforest range between 21 and 185 kg $m^{-2.}$ The lowest values of soil organic carbon are found on slopes of 18 °. Soil organic carbon content also exhibits a negative, linear relationship with slope with a decrease in soil organic carbon stock with increasing incline and a negative linear relationship with total annual rain days. The lower values of soil organic carbon occurs at sites experiencing 226 rain days per annum and the highest values of soil organic carbon occurs at sites experiencing 242 rain days per annum.

Montane rainforest

Organic carbon stocks under montane rainforest range between 17 and 237 kg m^{-2}, with the lowest values in soil organic carbon occurring at average daily maximum temperatures during the driest quarter of the year of 13.3° C and the highest values occurring at average daily maximum temperatures during the driest quarter of the year of 16.3° C.

Rainforest

Organic carbon stocks under rainforest range between 14 and 370 kg m^{-2}. A positive linear relationship exists between soil organic content and slope, total annual rain days and vegetation height. The upper range of soil organic carbon stocks is found on slopes of 20°, with the lower range occurring on gradients of around 5°. Soil organic carbon also increases with the total annual number of rain days with the

lowest values of soil organic carbon stocks found in sites with 244.9 rain days per annum and the highest values on sites experiencing 249.2 rain days per annum.
Soil organic carbon stocks exhibit a negative correlation with vegetation height as the lower range in soil organic carbon is found under the tallest vegetation.

6.3.2 General trends

The general trend is that organic soil carbon stocks follow topographic gradients with lower organic carbon stocks found on steeper slopes than in depressions or valleys. The exception to this is organic soil under rainforest where the highest organic carbon stocks are found on the steeper slopes. Slope therefore has an effect on all soil organic carbon stocks, although the nature and extent of the effect is not uniform across the vegetation type. The effect of slope is greatest on vegetation type on organic soils on dolerite or other nutrient-rich sites where there is a greater change in soil organic carbon stocks over a small change in slope, with organic soils only forming on slopes of 5° or less. The relationship between slope and soil organic carbon stocks under montane rainforest and coastal rainforest is less clear, but this could well be due to the lack of sampling across topographic locations. The effect of temperature is evident on soil organic carbon stocks, but only under certain vegetation communities. Rainforest exhibits a reduction in soil organic carbon stocks with an increase in average daily minimum and average daily maximum temperatures, with an optimum maximum daily temperature during the driest quarter of the year between 16 and 20°C while alpine communities and montane rainforest have a higher soil organic carbon stock with an increase in average daily maximum and average daily minimum temperatures, with an optimum maximum daily temperature during the driest quarter of the year between 12 and 14°C. Total annual rain days was found to positively influence soil organic carbon stocks under rainforest and coastal rainforest vegetation communities. The negative correlation between height of vegetation and soil organic carbon storage in rainforest and to a lesser extent, forest communities can be seen in Figure 6.7. There are also weak positive correlations between soil organic carbon storage and vegetation height in moorland, scrub and coastal forest communities.

6.3.3 Effects of ecological drift – succession

As burning regime was considered as a dummy variable, it did not play a significant part in the stepwise regression outputs. The most obvious reason for its lack of significance is that the effects of burning frequency and time since last burn are already implied in some of the broad vegetation groupings. Succession in vegetation, especially from moorland through scrub and wet eucalypt forest to rainforest is matched with a change in organic soil characteristics across the successional units. The effects of geology, additional nutrient input through regionality and proximity to coastal cyclic salts, climate and slope were isolated and the 4 successional stages were extracted from the data set for consideration of the effects of burning regime on soil organic carbon stocks. The sites that were considered were sampled across a fire boundary where the widths of the intermediate successional stages were narrower that the moorland and rainforest areas. The Mount Murchison site is in a high rainfall area, at 600 m a.s.l. and on slopes between 13° and 15° on nutrient poor Owen Conglomerate substrate. Significant differences in soil organic carbon stocks were found between the two successional extremes (Table 6.6, Figure 6.8), between moorland and scrub, scrub and wet eucalypt forest and scrub and rainforest, with wet eucalypt forest and rainforest not significantly different. The Port Davey Track site is also in a high rainfall area, at 340 m a.s.l. and on nutrient-poor quartzite substrate on a gentle slope of between 3° and 5°. Again, significant differences were found in soil organic carbon stocks across the vegetation types (Table 6.6, Figure 6.9), with significant differences in soil organic carbon found in soils under moorland / scrub communities and soils under wet eucalypt forest / rainforest communities. The Claytons site is also in a high rainfall area on the south west coast at 20 m a.s.l. on nutrient poor quartzite on slopes between 12° and 15°. Again, significant differences were found in soil organic carbon stocks between vegetation types (Table 6.6, Figure 6.10), apart from wet eucalypt forest and rainforest. The overall trend, when controlled for climate, geology and topography, is an increase in soil organic carbon stocks across fire boundaries from recent and/or frequently burnt vegetation through successional stages to not recently and /or infrequently burnt vegetation types.

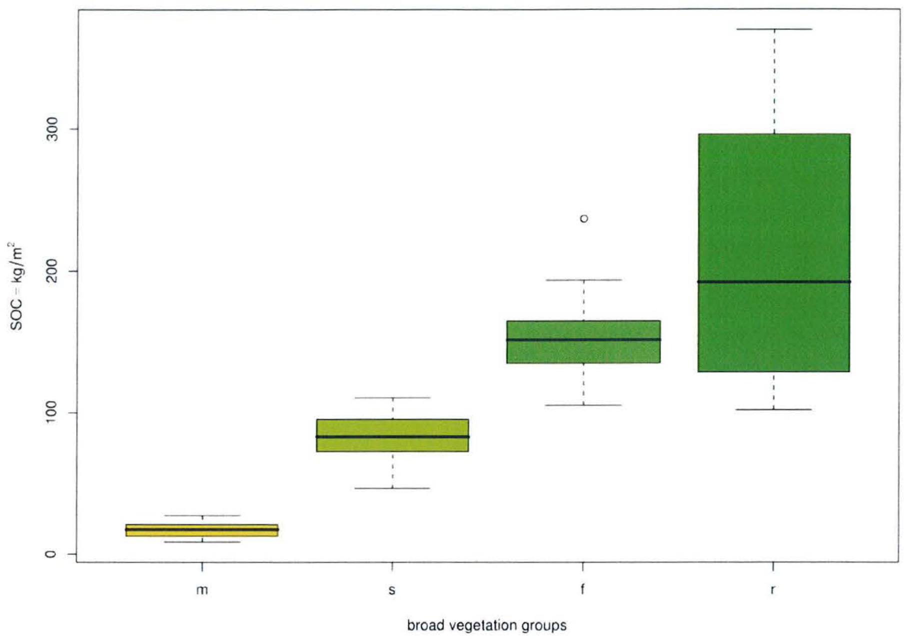

Figure 6.8

Soil organic carbon stocks in log kg of organic carbon per m^2 to total organic soil depth under buttongrass moorland (m), n = 20, scrub (s), n = 20, wet eucalypt forest (f), n = 20 and rainforest (r), n = 20. Substrate is quartzitic Owen Conglomerate on Mount Murchison in west Tasmania, gradient of slope between 13 and 15°. The median is represented by the solid black line within the green box, each end of the box is the first and third quartiles, the whiskers extend to the range times the interquartile range of the data extremes and the points are extreme outliers.

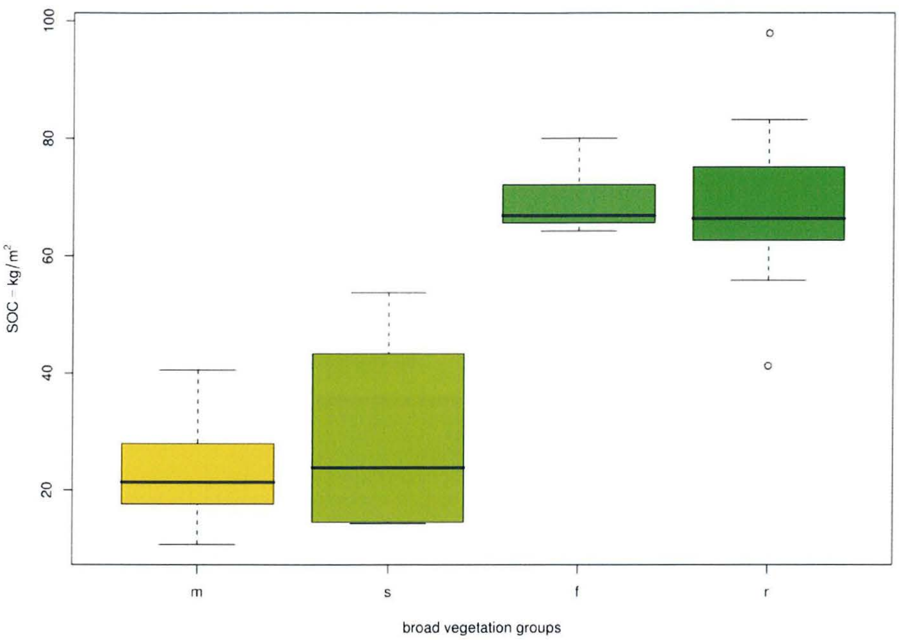

Figure 6.9

Soil organic carbon stocks in log kg of organic carbon per m^2 to total organic soil depth under under buttongrass moorland (m), n = 20, scrub (s), n = 20, wet eucalypt forest (f), n = 20 and rainforest (r), n = 20. The underlying substrate is quartzite along the Port Davey Track in south west Tasmania, gradient of slope between 3 and 5°. The median is represented by the solid black line within the green box, each end of the box is the first and third quartiles, the whiskers extend to the range times the interquartile range of the data extremes and the points are extreme outliers.

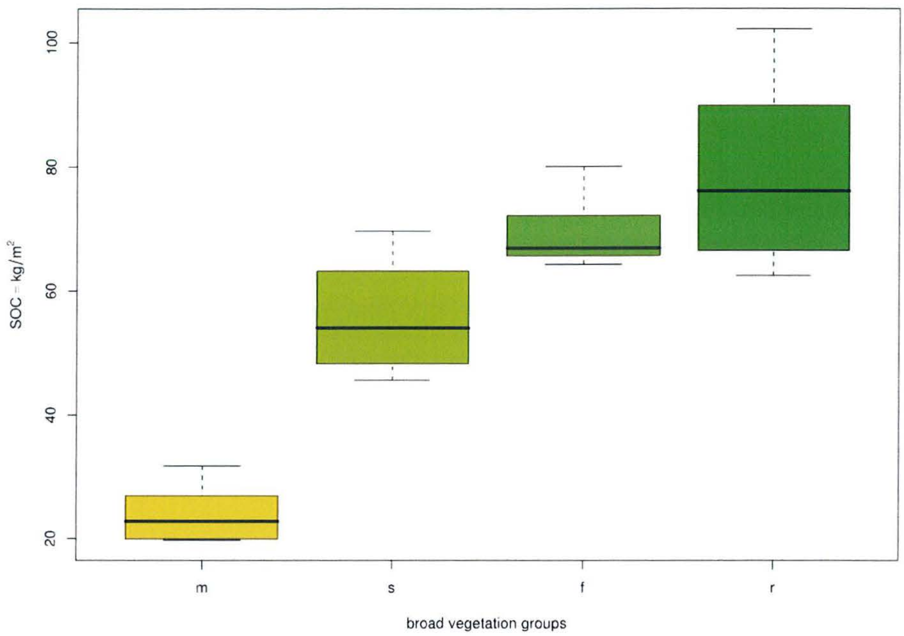

Figure 6.10

Soil organic carbon stocks in log kg of organic carbon per m^2 to total organic soil depth under buttongrass moorland (m), n = 20, scrub (s), n = 20, wet eucalypt forest (f), n = 20 and rainforest (r), n = 20. The underlying substrate is quartzite at Clayton's in south west Tasmania, gradient of slope between 12 and 15°. The median is represented by the solid black line within the green box, each end of the box is the first and third quartiles, the whiskers extend to the range times the interquartile range of the data extremes and the points are extreme outliers.

Table 6.6

Wilcoxon rank sum test significance for difference in soil organic carbon value (kg C m^2) between moorland (m), scrub (s), forest (f) and rainforest (r).

	m-s	*m-f*	*m-r*	*s-f*	*s-r*	*f-r*
Mount Murchison	3.6×10^{-10}	7.6×10^{-7}	7.6×10^{-7}	1.6×10^{-6}	8.0×10^{-7}	0.17
Port Davey track	1.000	0.003	6.5×10^{-5}	0.048	0.016	1.000
Claytons	0.0001	0.001	0.0001	0.009	0.001	0.14

6.3.4 Estimates of soil organic carbon stocks in Tasmanian organosols

An estimation of the amount of soil organic carbon held in organosols and tenosols in Tasmania can be made using the linear and generalised additive models above. In order to provide a representative estimation, model parameters need to be established as organosols occur within climatic limits.

Not considering the effects of topography, the climatic extremes for the locations of organosols found in Tasmania are detailed in Table 6.7 with the eastern mountains, eastern highland areas and southern coastal areas positioned in the least favourable climates for organic soil accumulation and the western upland areas providing the most favourable organic soil forming conditions.

Table 6.7

Data produced using BIOCCLIM (Busby 1986, Nix and Busby 1986, McMahon 1985). The maximum and minimum values are of all sites on which organosols were found. Lake Margaret is in the western mountain ranges, the eastern mountains are Mount Wellington, Ben Lomond and Snug Tiers. The Eastern Central Plateau is Pine Lake and Clarence. The west coast is Strahan, Ocean Beach, Trial Harbour and Birch's Inlet.

	maximum	*locations*	*minimum*	*locations*
total annual precipitation (mm)	3404	Lake Margaret	943	Eastern Central Plateau
total precipitation dry quarter (mm)	619	Lake Margaret	171	Eastern Central Plateau
total annual rain days	272	Lake Margaret	189	Eastern Mountains
total rain days dry quarter	52	Lake Margaret	35	Eastern Mountains
total annual precipitation – total annual evaporation (mm)	2654	Lake Margaret	240	Eastern Central

	maximum	locations	minimum	locations
				Plateau
total evaporation (mm)	913	Central Highlands, West Coast	640	Tyndall Range, Lake Margaret
total evaporation dry quarter (mm)	358	Central Highlands, West Coast	264	Tyndall Range, Lake Margaret
average daily maximum temperature (°C)	16	Central Highlands, West Coast	6.5	Ben Lomond
maximum daily temperature dry quarter (°C)	20.9	Central Highlands, West Coast	12.1	Ben Lomond

Isolated flats, experiencing no catchment runin were chosen to find a possible climatic boundary for organosol development, using lowest total annual precipitation. The lower boundaries are displayed in Table 6.8 along with the upper extreme measured.

Table 6.8

Climatic minimum and maximum measured for organosols in Tasmania, based on lowest and highest total annual precipitation (mm), without runin. Data produced using BIOCCLIM (Busby 1986, Nix and Busby 1986, McMahon 1985).

	Strahan	*Lake Margaret*
total annual precipitation (mm)	1626	3204
total precipitation dry quarter (mm)	279	573
total annual rain days	238	262
total rain days dry quarter	46	50
total evaporation (mm)	876	736
total evaporation dry quarter (mm)	343	298
average daily maximum temperature (°C)	15.4	11.5

	Strahan	*Lake Margaret*
maximum daily temperature dry quarter (°C)	19.2	16.3
total precipitation – total annual evaporation (mm)	750.5	2468

The total area covered by organosols is 8,974 km^2, the location and extent of which is shown in Figure 6.11. Most of the organosols occur in the west and south west of the state with organosols occurring in the central or east of the state restricted to high altitude sites.

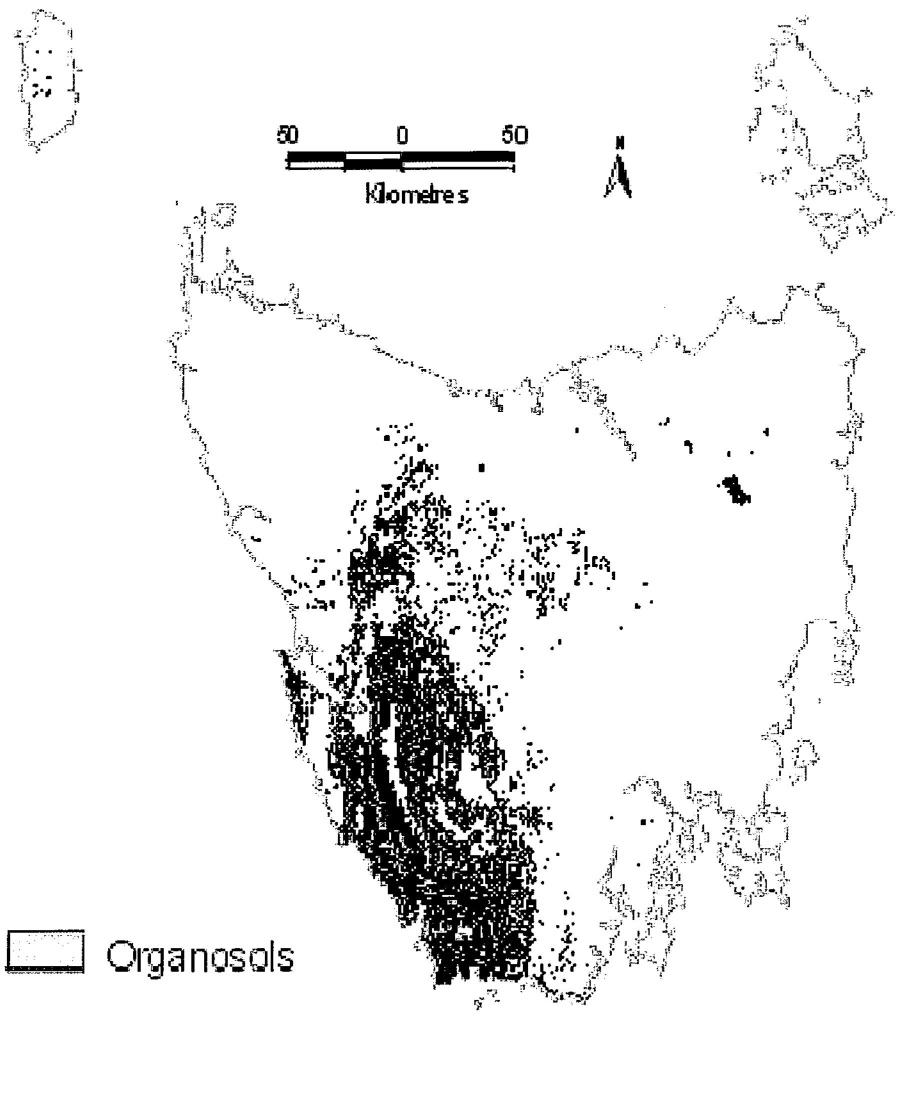

Figure 6.11

Distribution of organosols in Tasmania.

The total amount of soil organic carbon found in organosols is 3072 Tg. The amount of soil organic carbon for each vegetation type is provided in Table 6.9. The total amounts of soil organic carbon held under alpine on nutrient-rich geology, moorland, scrub and rainforest on nutrient-poor geology form the majority of the organic soil carbon held in organosols. The total stocks of carbon held in organosols are low under montane rainforest, alpine on low fertility substrate, moorland and rainforest on nutrient-rich geology, and vegetation close to the coast.

Table 6.9

Total organic carbon stocks found under the various vegetation classes used in the predictive mapping of SOC under organic soils in Tasmania.

Vegetation Class	*Area of organosol (km^2)*	*Soil organic carbon (million tonnes, Tg)*	Tg/km^2
alpine on nutrient-poor geology	60	13	0.22
alpine on nutrient-rich geology	494	563	1.14
moorland on nutrient-poor geology	3585	632	0.18
moorland on nutrient-rich geology	491	81	0.16
low altitude moorland close to coast	6	12	2
Scrub on nutrient-poor geology	1113	449	0.4
forest on nutrient-poor geology	1449	679	0.47
forest close to coast on nutrient-poor geology	68	19	0.28
rainforest on nutrient-poor geology	1511	567	0.38
rainforest close to coast on nutrient-poor geology	53	15	0.28
montane rainforest on all geology	144	43	0.3
Total	*8974*	*3072*	0.34

Although moorland on nutrient-poor geology provides the greatest areal extent of soil organic carbon, the greatest concentration of soil organic carbon per square kilometre is found on low altitude coastal moorland and on alpine on nutrient-rich geology (Table 6.9 and Figure 6.12). Moorland on nutrient-rich and nutrient-poor geology provide lower concentrations of soil organic carbon per kilometre squared compared with the other vegetation types, even though moorland on nutrient-poor geology covers the greatest areal extent (Table 6.9 and Figure 6.12).

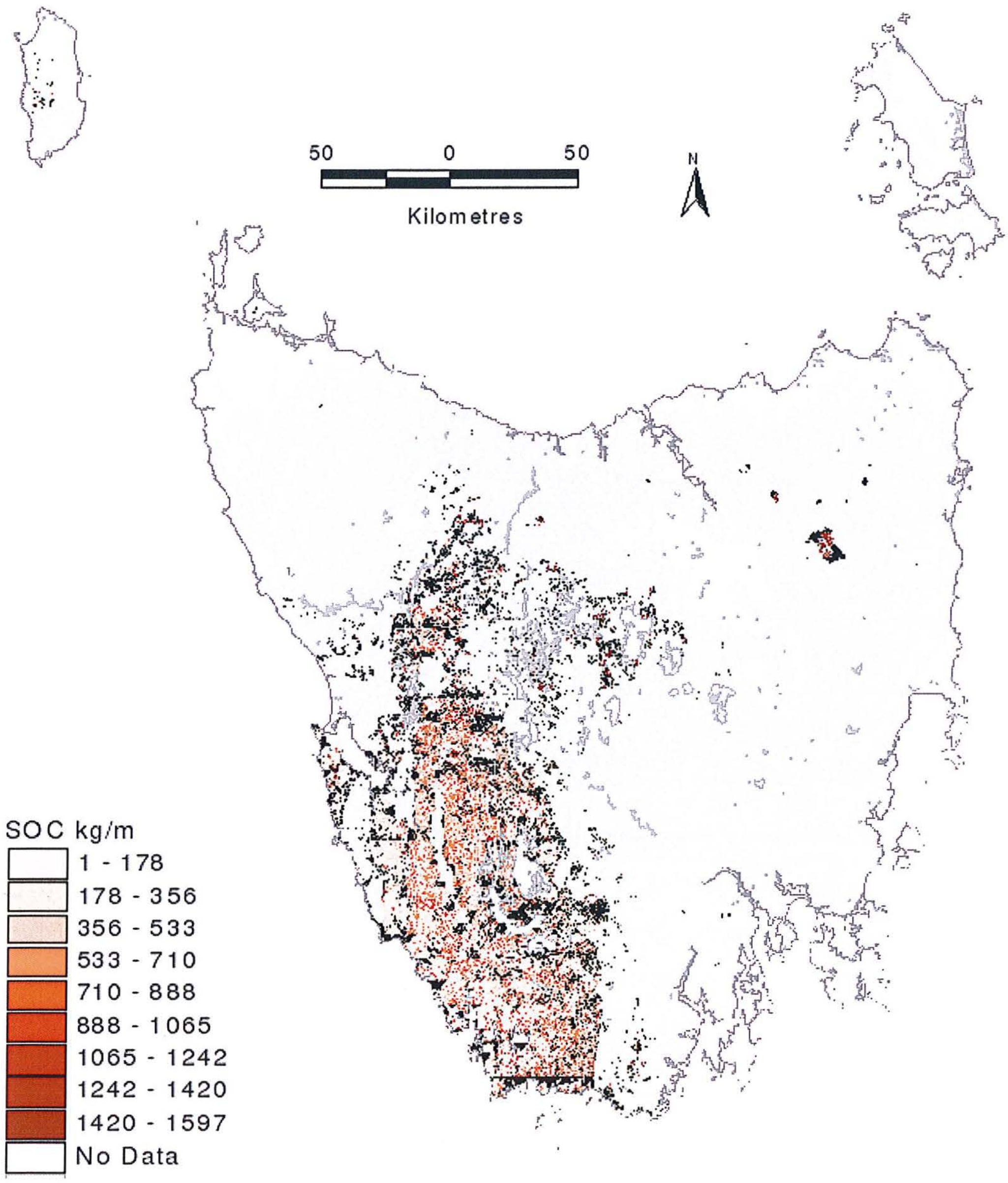

Figure 6.12: Predicted soil organic carbon content per metre squared in organic soils in Tasmania.

6.4 Discussion

The measurement and modelling of soil organic carbon in the soil order organosol can help in understanding soil organic matter accumulation processes and therefore provide a more process driven classification system. Estimates of current soil organic carbon stores are also important in providing a baseline data set against which future management and climate change impact can be assessed.

6.4.1 *Soil organic carbon modelling*

Modelling showed slope to be an important variable in influencing soil organic carbon through the influence of depth on the total organic carbon stocks found under one metre squared. Although the overall effect of slope is only $R^2 = 0.24$, the effect of other soil forming factors on organic matter accumulation can be isolated when the data set is divided into broad vegetation groups by climate and geology. This division has the effect of isolating productivity classes based on the productivity of the vegetation itself, the influence of underlying substrate on productivity, the influence of climate on productivity, the influence of nutrient input from cyclic salts due to the proximity to the coast and also isolating fire regimes which influence both vegetation productivity and nutrient availability in the soil. The results of the primary divisions in the vegetation and geology have been to highlight the influence of slope and topography on soil organic carbon accumulation. In all vegetation types, apart from rainforest, coastal rainforest and montane rainforest, organic soil accumulation follows a catena, which has been recognised in other soil type around the world and is included in classification systems.

The influence of slope on soil depth has been noted in other soil types, as well as peat, with a decrease in soil depth with slope gradient (Franzmeier and Whiteside 1963, Post *et al.* 2001, Tate *et al.* 2004, Thompson and Kolka 2005). Organic carbon accumulation has also been noted as being influenced by slope and topographic position (Furley 1968, Jordan 1974, English 1977, Clymo 1984, Post *et al.* 2001, Hao *et al.* 2006), with both slope and topographic position influencing both drainage patterns and water table and thus soil organic carbon accumulation and decomposition.

The influence of topography is especially noticeable on organosols on dolerite which are only found in topographic depressions in high rainfall and/or low temperature areas which inhibit decomposition of accumulating organic matter, or in sloping fens, springs and flushes where the water table is maintained, creating reducing conditions and a slowed decomposition of organic material. Where the water table and/or drainage does not create reducing conditions on dolerite, mineral soils occur. Examples of this sharp gradient can be can be seen at Mount Field where small patches of *Sphagnum* organic soils follow seepage lines alongside mineral soil, and on buttongrass moorland at King William Plains where organic soils grade to mineral soils on slopes of only 5°. Moorland on nutrient-poor substrate produces a curvilinear model with soil organic carbon and slope. The non-linear response is probably due to the cut-off value for slope at 0°, which does not differentiate between flat ground and depressions. A wetness index model, (for example, Sørensen *et al.* 2006) which relates slope position and soil wetness would be more appropriate, especially in relation to buttongrass moorland on nutrient-poor geology, as organosols have been found over a wide range of slope gradients under this vegetation class. Using only slope is still a reasonable estimate, as slope shape and position affects drainage and soil wetness with succession from moorland to forest vegetation. In northern organic soils (for example, Laine *et al.* 1995, Minkkinen and Laine 1998) succession from moorland to forest has been shown to be attributable to drainage. Succession from moorland through scrub, wet eucalypt forest and rainforest has been shown to lower the probability of fire in Tasmania (Jackson 1968, Brown and Podger 1982, Jarman *et al.* 1982). Scrub and forest vegetation provides greater cover and greater above and below-ground biomass than moorland, thus providing better protection against the effects of waterlogging and drought than moorland. The mosaic of successional vegetation types on concave and convex slopes of similar geology and slope gradient show existing edaphic boundaries can be maintained through the interaction of fire frequency and drainage (Brown and Podger 1982). When the data set is divided by vegetation type, the moorland will occur on convex slopes with scrub and wet eucalypt forest on concave slopes (Plate 6.1). Despite this generalisation regarding slope, a wetness index of topographic position, slope gradient and slope length would be preferable for buttongrass moorland on nutrient-poor geology and may produce a more linear relationship with better correlation between topography and soil organic carbon content, but more importantly, would include the effect of depressions and slope shape in the modelling.

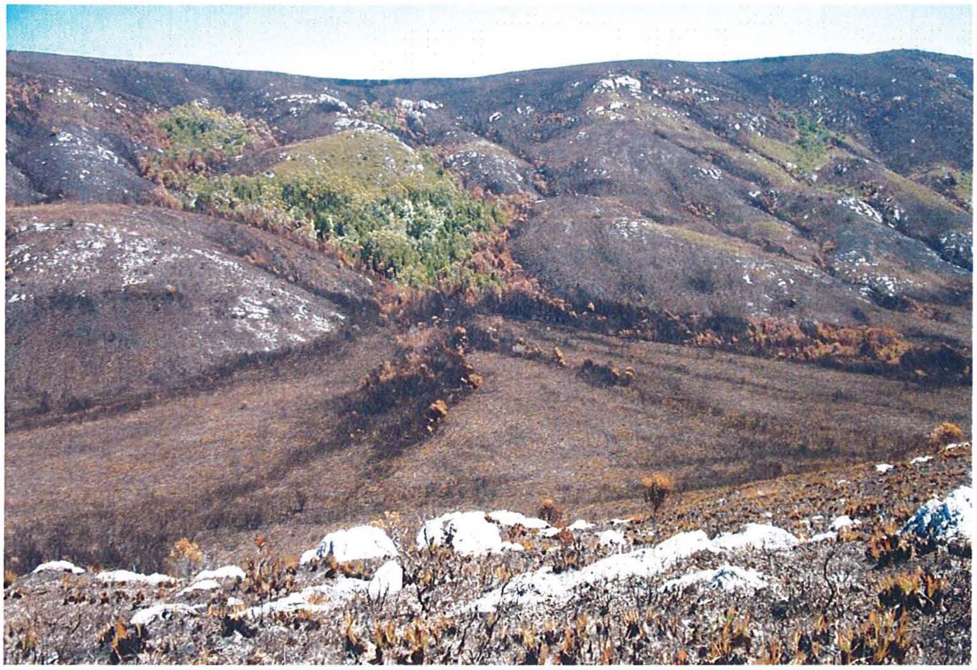

Plate 6.1

Twelvetrees Range, Tasmania. Buttongrass burned in foreground and on convex slopes with scrub and wet eucalypt forest unburned on concave slopes.

Organic soil was not generally found under rainforest in valleys. Rather, mineral soils were more likely to develop from washed-in phyllite clay, resulting in a higher productivity and a more rapid succession after fire. Organic soils under rainforest, on nutrient-poor substrate, were found only on slopes of between 2° and 25°. There were limited examples of rainforest occurring on nutrient-poor substrates, with sites occurring in fire protected situations and on islands. The positive correlation with slope may therefore reflect fire protection rather than wetness. Deeper organic soil deposits under rainforest were found in higher rainfall, but well-drained sites, which may be due to low microbial action and decomposition and high productivity and therefore high organic matter accumulation rates.

The higher productivity of forested organic soils, compared with the surrounding moorland organic soils, has been found to offset increased aeration of organic soils underlying forests in Finland (Laine *et al.* 1995), but rainfall (Reinikainin 1981, Laiho and Finér 1996, Laiho and Laine 1997, Minkkinen and Laine 1998, Schuur *et al.* 2001) and temperature (Clymo *et al.* 1998) have been found to affect the soil organic carbon storage potential of forested organic soils.

A lower limit for wetness may be possible for organic soil development in Tasmania, with a lower rainfall, also in conjunction with higher temperatures, increasing microbial action and stimulating organic decomposition (Chmielewski 1991), as can be seen in coastal rainforest on nutrient-poor status substrates (Figures 6.2 – 6.7) even though productivity may be high. An upper wetness limit would restrict productivity, even though decomposition is limited through waterlogging (Moore and Bellamy 1974, Clymo 1984, Laine *et al.* 1995, Lindsay 1995). Although sample numbers are limited, these thresholds may exist in the data (Figures 6.2 – 6.7) where soil organic carbon seems to reach a limit on organic soils on low nutrient status substrate under rainforest, scrub and moorland with higher rainfall. It would seem therefore that recovery in soil nutrients and soil organic matter accumulation after fire is controlled by both productivity and decomposition which are, in turn, affected by waterlogging and drought.

Waterlogged conditions inhibit productivity, although decomposition is reduced, while drought inhibits productivity, and decomposition is increased (Clymo 1984, Post *et al.* 1982, Olson *et al.* 1983, Zinke *et al.* 1983). Waterlogging on substrates with a high nutrient status seems to produce deep soil organic carbon stocks where decomposition is limited, but productivity remains high through rheotrophic mineral supply. In extreme waterlogged conditions, *Sphagnum* species, *Empodisma minus*, *Gleichenia* species and cushion plant species occur, producing deep, organic carbon rich deposits.

Low temperatures are the soil organic carbon reducing factor in the waterlogged nutrient-rich substrates, with lower temperatures known to reduce both productivity and microbial activity (Buckman and Brady 1960, Clymo *et al.* 1998). This can be seen in Figure 6.4, where higher average daily maximum temperatures produce greater soil organic carbon stocks in waterlogged higher nutrient status alpine areas. Above the treeline on lower nutrient substrate, temperature also seems to limit productivity with low soil organic carbon stocks due to shallow organic soil accumulation depths. Deeper deposits occur under cushion plants and in sheltered positions, in cracks and crevices and on gentle gradients where productivity is higher. Average daily minimum temperature and average maximum daily temperature also influences soil organic carbon storage in rainforest, scrub and montane rainforest on nutrient-poor substrate. Soil organic carbon stocks are reduced with an increase in both average daily maximum and average daily minimum temperature under rainforest, which may be due to the increased microbial decomposition rates and increased evapotranspiration under slightly higher temperatures (for example, Chmielewski 1991, Bridgham *et al.* 1991, Hogg *et al.* 1992). However, soil organic carbon stocks increase with increasing temperature under both montane rainforest and scrub. Here, vegetation type follows a temperature gradient with rainforest on the lower altitude sites through montane rainforest, subalpine and alpine vegetation with increasing altitude and decreasing temperatures. Productivity reduces with decreasing temperatures, thus producing lower organic soil stocks. Soil organic stocks on nutrient-poor geology under scrub vegetation are also greater with an increase in temperature, probably through increased productivity and therefore protection from fire through a more rapid succession from buttongrass moorland after fire (Jackson 1968, Brown and Podger 1982, Jarman *et al.* 1982).

The influence of proximity to the coast should, however, not be overlooked with regards to its effect on the processes of organic soil accumulation and decay, with increased productivity through higher temperatures (although temperatures are less extreme in coastal areas, with lower temperatures in summer and higher temperatures in winter than inland areas), additional nutrient input through precipitation and the increased time of soil development after the last glacial. Both coastal and inland low-lying glacial outwash plains have produced ideal conditions for well-drained sites on gravel rises on sandar. Deep organic soil mounds have formed and where the surrounding buttongrass will burn in wetter conditions than the scrub communities found on the sandur mounds. This positive feedback effect is also evident in slope position where protection from either waterlogging and/or drought has the effect of increasing productivity and hastening the succession from buttongrass moorland to scrub communities (Brown and Podger 1982, Jarman *et al.* 1982).

The strong effects of slope, rainfall and temperature on Tasmanian organic soil carbon stocks are evident through the high levels of predictability displayed in the interactions of fire frequency, drainage, geology and climate on Tasmanian vegetation. The well-developed pattern of vegetation mosaics has allowed for a high correlation between the predictors of slope and climate with the response of soil organic carbon. The effects of fire frequency have been well discussed in terms of moorland, scrub, wet eucalypt and rainforest vegetation communities for Tasmania (Jackson 1968, Brown and Podger 1982, Jarman *et al.* 1982) and in terms of the effect of burning on organic soils (Radley 1962, Swanson 1981, Wein 1983, Maltby *et al.* 1990). For organic soils in Tasmania, the effects of burn frequency needed to be assessed when controlled for underlying substrate, climate and topography in order to isolate, as far as possible, through observation, the main soil organic carbon accumulating factors. It is clear from the results that succession through absence of fire results in an increase in soil organic carbon from moorland through to rainforest (Figures 6.8 – 6.10). The effects of fire on organic soils elsewhere appear to be related to the vegetation type in question (see Lindsay 1995 for an overview). Although alpine and subalpine areas were not assessed for the influence of fire separately, complete removal of the organic soil was visible on Mount Murchison and the Tyndall Range, resulting in different species assemblages from unburnt areas, especially on well-drained sites. The effects of fire on alpine and sub-alpine soils has been reported in the literature (Kirkpatrick and Dickinson 1984a, Kirkpatrick *et al.* 2002) and its effect on high mountain endemic vegetation recovery, shrub cover and therefore productivity would suggest that soil organic carbon stocks are lowered as a result of fire in the alpine and sub-alpine areas, especially in well drained sites, where complete removal of the organic soil through erosion after fire has been recorded (Kirkpatrick and Dickinson 1984a).

6.4.2 Soil organic carbon stores

Organosols cover approximately 40% of the land surface area of Tasmania with the total amount of soil organic carbon at 3072 Tg. This figure is difficult to compare with other results (Table 6.8), as only a few models include soils to their total depth. The depth restriction is largely due to the agricultural use of the soils under investigation, and the reduced amount of carbon found in non-organic soils under 1 metre from the soil surface. The ECOSSE model (Estimating Carbon in Organic

Soils Sequestration and Emissions) (Scottish Executive 2007) in Scotland report 2,735 Tg of soil organic carbon to total depth for organic soils. The inclusion of "lithic" organosols in the model was important as these form the "skeletal" soils referred to in the Tasmanian literature (Pemberton 1989) and are not currently classifiable under the Australian Soil Classification. Suggestions are made in Chapter 7 on how to treat the "lithic" organosols as there is a (slope) catena between them and organosols which needs to be considered. The "lithic" organosols, found under buttongrass moorland, cover a large area of Tasmania and despite the moderate concentrations of organic soil found under inland buttongrass moorland on low nutrient geology, their extensive coverage makes these classes important contributors to carbon stocks in Tasmania.

Table 6.8

Comparative soil organic carbon stocks from predictive models. SOC = soil organic carbon in Tg.

Location	*Depth considered from surface*	*SOC*	*Source*
Scotland (organic soils)	1 m	2 187	Bradley *et al.* (2005)
Scotland (organic soils)	to depth	2 735	Scottish Executive. (2007)
Tasmania (organosols and "Lithic" organosols only)	to depth	3 072	Present study
Wales (organic soils)	to depth	196	Scottish Executive. (2007)
UK (organic soils)	1 m	4 560	Bradley *et al.* (2005)
UK (organic soils)	6 m	9 800	Milne *et al.* (1997)
Global (all soils)	1 m	1 500 000	IPCC (2001)
NZ (grazing land only)	0.3 m	1 480	Tate *et al.* (2004)
NZ (remnant indigenous forests only)	0.3 m	1 140	Tate *et al.* (2004)

6.4.3 *Implications for classification*

Although soil taxonomic systems, including the Australian Soil Classification (Isbell 2002) and the World Reference Base for Soil Resources (FAO 2006), classify soils using diagnostic horizons, properties, and materials, these systems are based on genetic principles. The approaches used have de-emphasized the role of soil processes in soil taxonomic systems, but a consideration of soil processes is important for understanding the genetic underpinnings of modern soil taxonomic systems and for developing quantitative models of pedogenic systems. An understanding of the processes of organic soil accumulation is vital in any suggested changes to the Australian Soil Classification. The success in the ability to predict organosol location and extent through modelling of the processes under which they form, will serve to inform decisions made in choosing further differentiae. The success of the current Australian Soil Classification in predicting the quantitative clusters found in Chapters 4 and 5 is assessed in Chapter 7 and suggested changes to the current differentiae in the order organosols are made.

Chapter 7

Classification comparison and suggested changes to the Australian Soil Classification

7.1 Introduction

Quantitative methods for characterising Tasmanian organic soils are used in Chapter 3 and Chapter 5, which produce soil classification units based on intrinsic soil properties and dominant environmental factors affecting organic soil characteristics. Some properties that have been used to characterise and classify organic soils and thus produce differentiae in other taxonomic systems, have not been useful for Tasmanian organic soils. Tasmanian organic soils occur under vegetation and in landscapes that do not always have an international correlate and therefore it is no surprise that some of the differentiae used in soil taxonomies are not important in defining Tasmanian organic soils, while some informative and representative differentiae are missing. The preferred classification would be that produced in Chapter 3, with a geographic classification produced in Chapter 5 and a mapping and genesis classification produced in Chapter 6 informing the location, extent and depth of organic deposit. It was suggested that a classification should be mappable (Smith 1983, Isbell 2002), which has been achieved using the classifications produced in chapters 4, 5 and 6.

The soil pit data from Chapters 3 and Chapter 5 are used to assign each soil pit to the corresponding WRB, Soil Taxonomy and Australian Soil Classification units. The effectiveness of these classifications in describing Tasmanian organic soils is assessed and suggestions for improvements to the current differentiae are suggested and assessed. The current organic soil landform terminology and its applicability to Tasmanian organic soil landforms are also discussed with suggestions for revision and/or improvement to current definitions.

7.2 Methods

7.2.1 Statistical analysis

The supervised and unsupervised clusters are compared with the current method of classifying organic soils in Australia and the World Reference Base for Soil Resources. Each soil pit is assigned to a soil group using the methods described in Isbell (2002) for the Australian Soil Classification and the methods described in the World Reference Base for Soils (FAO 2006). The Australian Soil Classification is used to classify the soil pits to both suborder level and to family level in order to assess the first level of the hierarchy and also the ability of the lowest level of the hierarchy to characterise organic soils. The World Reference Base for Soil Resources is used to assign qualifiers to the soil group organosol using the qualifiers provided for the histosol reference soil group. Comparisons between the Australian Soil Classification, the WRB and both the supervised clusters and unsupervised clusters produced in Chapters 4 and Chapter 5 respectively, are made using the compareClass function in the mclust package in R 2.2.1. This compares cluster association using a normalised variation of information criterion (Meila 2002). Non-metric multi- dimensional scaling ordination plots produced in Chapter 4 are used to highlight the effectiveness of the Australian and WRB in describing the edaphic factors and variables in Tasmanian organic soils.

7.2.2 Suggestions for changes to the Australian Soil Classification order organosol.

Changes to the Australian Soil Classification (Isbell 2002) are necessary to adequately describe the character of the Tasmanian organic soils. Suggestions are made on the basis of the results produced in Chapters 4, 5 and 6 and are dealt within the discussion section.

7.2.3 Comparisons with landform classifications.

Due to the lack of consensus in the literature as to the definitions of landform elements which produce organic accumulating landforms, no statistical assessment was possible. Rather, a description of the landforms and geographical settings under which organic soils in Tasmania are found and how these characteristics may compare to international definitions is provided in the discussion section.

7.3 Results

Neither the WRB, nor the Australian Soil Classification performed well in predicting the supervised or unsupervised clusters (Table 7.1, Figures 7.1 to 7.4). For the Australian Soil Classification, the supervised clusters were predicted slightly better than the unsupervised clusters with a class error of 65% for the unsupervised clusters, compared with 53% class error for the supervised clusters. For the WRB, both supervised and unsupervised clusters were predicted at a class error of 66%.

Table 7.1

Values of normalised variation of information criterion using mclust package in R 2.2.1. Unsupervised clusters and supervised clusters produced in Chapter 4 and Chapter 5 respectively. wrb = World Reference Base (WRB) for soil resources (FAO 2006), wrbo = using only one of fibric, hemic, sapric, folic, lignic, aus = Australian Soil Classification (Isbell 2002), auso = Australian Soil Classification only to suborder level, newo = using 4 new differentiae to the Australian Soil Order organosol to the subgroup level, new = using 4 new differentiae to the Australian Soil Order organosol to the subgroup level and possible family criteria.

	unsupervised clusters	*supervised clusters*	*wrb*	*wrbo*	*aus*	*auso*	*newo*	*new*
unsupervised clusters	0	0.23	0.43	0.42	0.43	0.43	0.19	0.04
supervised clusters	-	0	0.38	0.42	0.34	0.43	0.33	0.05
Wrb	-	-	0	-	0.21	-	-	-
Wrbo	-	-	-	0	-	0.01	-	-

The assignation of the unsupervised clusters produced in Chapter 3 to Australian soil orders, suborders, great groups, subgroups and families are shown in Table 7.2, with the primary division of organosol into the suborder fibric, hemic and sapric, followed by divisions into great groups of folic and acidic. The pH limit for acidic is pH_{CA} of 4.6 which placed all the soils under the great group acidic. The subgroups used were lithic, rudaceous, modic, terric and regolithic. The family criterion used was the cumulative thickness of the organic materials. The unsupervised clusters 6, 7, 8 and 9 were not classed as organosols due to depth limits and are therefore classified under the soil order tenosol. The assignation of the organic soil pits to WRB reference soil groups are shown in Table 7.2 with only the prefix qualifiers; folic, lignic, fibric, hemic, sapric and leptic relevant. Supervised cluster 6, 7, 8 and 9 were also not classed as histosols, but were assigned to the reference soil group, leptosol. The first hierarchical level for organosols in the Australian Soil Classification is to differentiate fibric, hemic and sapric peat. Table 7.1 and Figure 7.3 show a low classification correlation between the unsupervised clusters and the assignation into three groups based solely on humification with a class error of 76%. The WRB qualifiers folic, lignic, fibric, hemic and sapric also perform poorly in predicting the unsupervised clusters (Table 7.1 and Figure 7.4) with a classification error of 74%.

Table 7.2

Assignations of both the World Reference Base (WRB) for soil resources (FAO 2006) and the Australian Soil Classification (Isbell 2002) soil groups for the unsupervised clusters produced in Chapter 4. The codes used here are the shortest possible for use on the plots and are not the codes provided in the WRB or the Australian Soil Classification.

unsupervised clustering	*wrb codes*	*wrb qualifiers*	*aus codes*	*aus*
1	Lg	lignic	ffalm	fibric folic acidic lithic moderate
2	Lg	lignic	ffarm	fibric folic acidic rudaceous moderate
3	Fohm	folic hemic	hfareth	hemic folic acidic regolithic thick
4	Fohm	folic hemic	hfalm	hemic folic acidic lithic moderate
5	Lgle	lignic leptic	ffarvt	fibric folic acidic rudaceous very thin
6	O	leptosol	o	tenosol
7	O	leptosol	o	tenosol
8	O	leptosol	o	tenosol

unsupervised clustering	*wrb codes*	*wrb qualifiers*	*aus codes*	*aus*
9	O	leptosol	o	tenosol
10	Lgle	lignic leptic	farvt	fibric acidic rudaceous very thin
11	fohm	folic hemic	hfarm	hemic folic acidic rudaceous moderate
12	Fohmle	folic hemic leptic	sarm	sapric acidic rudaceous moderate
13	Lgsa	lignic sapric	sfarvth	sapric folic acidic rudaceous very thick
14	Fi	fibric	famm	fibric acidic modic moderate
15	Sa	sapric	samvth	sapric acidic modic very thick
16	Hm	hemic	harm	hemic acidic rudaceous moderate
17	Sa	sapric	sarth	sapric acidic rudaceous thick
18	Sale	sapric leptic	sart	sapric acidic rudaceous thin
19	Sa	sapric	hamm	hemic acidic modic moderate
20	Fi	fibric	famm	fibric acidic modic moderate
21	Sale	sapric leptic	sart	sapric acidic rudaceous thin
22	Fohmle	folic hemic leptic	hart	hemic acidic rudaceous thin
23	Sa	sapric	sarm	sapric acidic rudaceous moderate

The assignation of the unsupervised clusters to both the Australian Soil Classification classes and the World Reference Base for Soil Resources reference soil groups are displayed in Table 7.3 and Figures 7.2 and 7.4. The differentiae and qualifiers are the same as those described in the supervised clustering above. The classification error was also high (Table 7.1) with 53% classification error in predicting the unsupervised clusters for the Australian Soil Classification and 66% classification error in predicting the supervised clusters for the WRB. Table 7.1 and Figure 7.4 show a low classification correlation between the supervised clusters and the first differentiae of three groups based solely on humification under organosol, with a class error of 78%. The WRB qualifiers folic, lignic, fibric, hemic and sapric also perform poorly in predicting the supervised clusters (Table 7.1 and Figure 7.3) with a classification error of 76%.

Table 7.3

Assignations of both the World Reference Base (WRB) for soil resources (FAO 2006) and the Australian Soil Classification (Isbell 2002) soil groups for the supervised clusters produced in Chapter 5. wrb = World Reference Base for soil resources codes and associated qualifiers, aus = Australian Soil Classification codes and associated differentiae for suborder, great group, subgroup and family codes and associated differentiae for suborder, great group, subgroup and families and associated differentiae for suborder, great group, subgroup and family. The codes used here are the shortest possible and are not the codes provided in the WRB or the Australian Soil Classification.

supervised clustering	*wrb code*	*wrb qualifiers*	*aus code*	*aus differentiae*
A1	Hm	hemic	famth	fibric acidic modic thick
A2	Fi	fibric	famm	fibric acidic modic moderate
A3	Fi	fibric	famm	fibric acidic modic moderate
A4	Sa	sapric	hamth	hemic acidic modic thick
A5	Sa	sapric	Hamt	hemic acidic modic thin
A6	Hmle	hemic leptic	Hamt	hemic acidic modic thin
A7	Sa	sapric	samt	sapric acidic modic thin
A8	Fole	folic leptic	farvt	fibric acidic rudaceous very thin
A9	fohmle	folic hemic leptic	hart	hemic acidic rudaceous thin
B1	fohmle	folic hemic leptic	farvt	fibric acidic rudaceous very thin
B2	O	leptosol	o	tenosol
B3	O	leptosol	o	tenosol
B4	Sale	sapric leptic	sart	sapric acidic rudaceous thin
B5	Sale	sapric leptic	o	tenosol
B6	fohmle	folic hemic leptic	hart	hemic acidic rudaceous thin
B7	Sale	sapric lepric	sart	sapric acidic rudaceous thin
B8	Sa	sapric	sarm	sapric acidic rudaceous moderate
BC1	O	leptosol	o	tenosol
BC2	Sa	sapric	samm	sapric acidic modic moderate

supervised clustering	*wrb code*	*wrb qualifiers*	*aus code*	*aus differentiae*
BC3	Hmle	hemic leptic	hart	hemic acidic rudaceous thin
BM	Fosa	folic sapric	sarm	sapric acidic rudaceous moderate
BR1	sa	sapric	harm	hemic acidic rudaceous moderate
BR2	Sa	sapric	sarvt	sapric acidic rudaceous very thin
F1	O	leptosol	o	tenosol
F2	Lg	lignic	ffarm	fibric folic acidic rudaceous moderate
N1	Lgle	lignic leptic	hfart	hemic folic acidic rudaceous thin
R1	Lg	lignic	ffatm	fibric folic acidic terric moderate
R2	Lgle	lignic leptic	ffatvt	fibric folic acidic terric very thin
R3	Lg	lignic	ffalm	fibric folic acidic lithic moderate
R4	Fohm	folic hemic	hfalm	hemic folic acidic lithic moderate
R5	Lgle	lignic leptic	ffart	fibric folic acidic rudaceous thin
R6	Lghm	lignic hemic	hfarm	hemic folic acidic rudaceous moderate
R7	O	lithosol	o	tenosol
R8	Lgle	lignic leptic	hfatt	hemic folic acidic terric thin
R9	Lgle	lignic leptic	hfalm	hemic folic acidic lithic moderat
S1	Fohm	folic hemic	hfareth	hemic folic acidic regolithic thick
S2	Sa	sapric	harm	hemic acidic rudaceous moderate
S3	Sa	sapric	sareth	sapric acidic regolithic thick

supervised clustering	*wrb code*	*wrb qualifiers*	*aus code*	*aus differentiae*
S4	Fohm	folic hemic	harm	hemic acidic rudaceous moderate
S5	Lgsa	lignic sapric	sfarvth	sapric folic acidic rudaceous very thick

7.3.1 Suggested changes to Australian Soil Classification differentiae

The rationale behind the suggested changes to the order organosol within the Australian Soil Classification system is given in the next section. The additions of folic, lignic, arenic and argillic to the differentiae for the order organosol are shown in Table 7.4. The classification error is reduced to 33% through the addition of these 4 differentiae at a sub-group level (see Figure 7.5). The assignation of class using differentiae would follow the rules for classification already laid out in the Australian Soil Classification (Isbell 2002) of eliminating differentiae in the order given, as they are laid out in columns in order of importance. It is also suggested that more than one differentiae should be able to be selected from each column, as folic materials can be fibric, hemic or sapric, and waterlogged organic soils also exhibit the range of humification in the dominant horizon. This may not be desirable, but the necessity to integrate with international classification systems does not allow for a dramatic rearrangement of the differentiae, and this compromise seems reasonable. If the suggested family criteria were accepted, it would be possible to assign the organosols to the unsupervised clusters with < 5% error in classification, but only when the soil pits had first been assigned to the unsupervised clusters.

Table 7.4

Revised differentiae for the Australian Soil order, organosol.

suborder	*great group*	*sub group*	*Possible family criteria*
folic	lignic	argillic	Humification of surface tiers
fibric	sulfuric	arenic	
hemic	sulfudic	lithic	Cumulative thickness of organic
sapric	calcareous	rudaceous	horizons
	basic	siltic	
	acidic	modic	Botanical composition of surface
		terric	layers
		placic	
		ashy	Botanical composition of dominant
		regolithic	layers
		paralithic	
			acidity classes below pH_{CA} 4.6

Table 7.5

Assignations of the revised differentiae for the Australian Soil order, organosol to subgroup level. The codes used here are the shortest possible for use on the plots and are not the codes provided in the WRB or the Australian Soil Classification.

unsupervised clusters	*Suggested Australian classification*	*Suggested Australian Classification code*
1	folic fibric lignic	fofilg
2	folic lignic lithic	folgli
3	folic hemic lignic	fohelg
4	folic hemic lignic lithic	fohelgli
	folic lignic arenic	folgare
5	folic lithic	foli
6	folic lithic	foli
7	folic sapric rudaceous	fosaru
	folic hemic rudaceous	foheru
8	folic hemic lithic	foleli
	folic sapric rudaceous	fosaru
9	folic sapric argillic	fosaarg
	folic lignic lithic	folgli
10	folic lignic arenic	folgare
11	folic hemic	fohe
12	folic sapric	fosa
	folic sapric lignic	fosalg
13	folic hemic lignic	fohelg
	fibric argillic	fiarg
14	hemic argillic	hearg
15	sapric	sa
16	hemic	he
17	sapric	sa
	hemic lithic	heli
18	sapric lithic	sali

unsupervised clusters	*Suggested Australian classification*	*Suggested Australian Classification code*
19	sapric arenic	saare
	hemic argillic	hearg
20	fibric argillic	fiarg
21	sapric argillic	saarg
22	sapric rudaceous	saru
23	sapric siltic	sasi

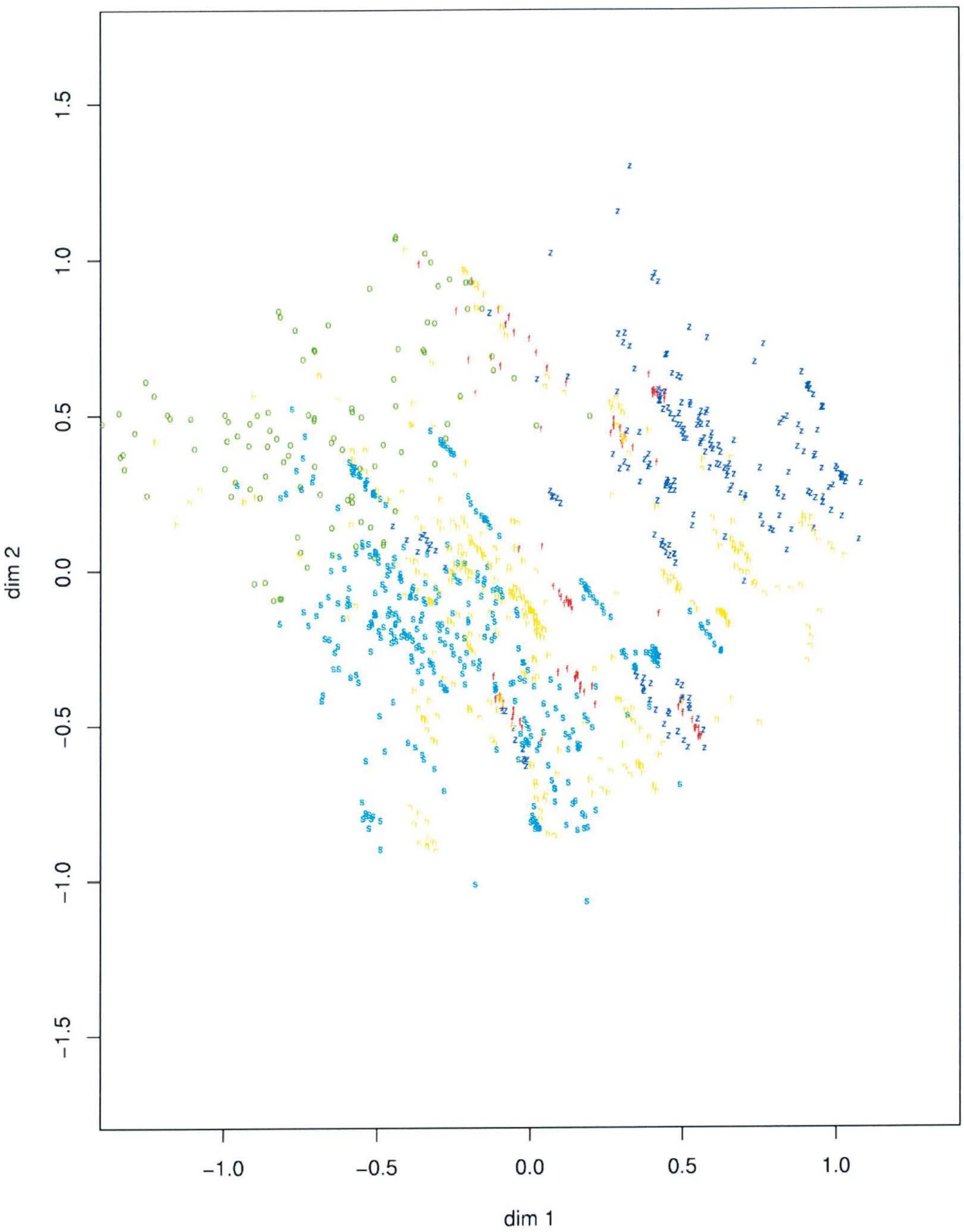

Figure 7.1

NMDS ordination plot of intrinsic soil characteristics as in Chapter 3 with individual soil pits labelled according to WRB fibric (f), folic (z), hemic (h), sapric (s) classes, with lithosols displayed (o).

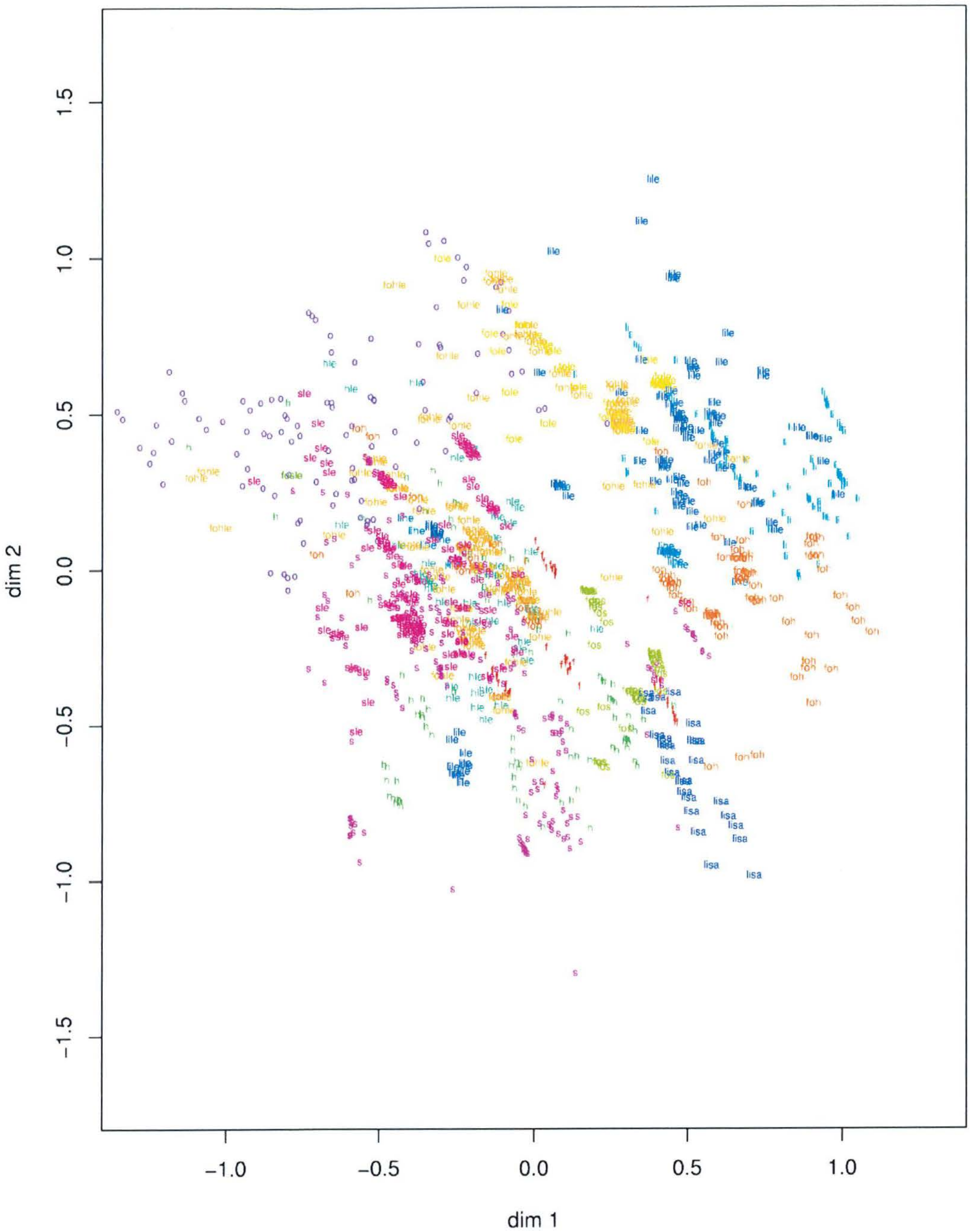

Figure 7.2

NMDS ordination plot of intrinsic soil characteristics as in Chapter 3 with individual soil pits labelled according to WRB RSG and qualifiers as defined in Table 7.2.

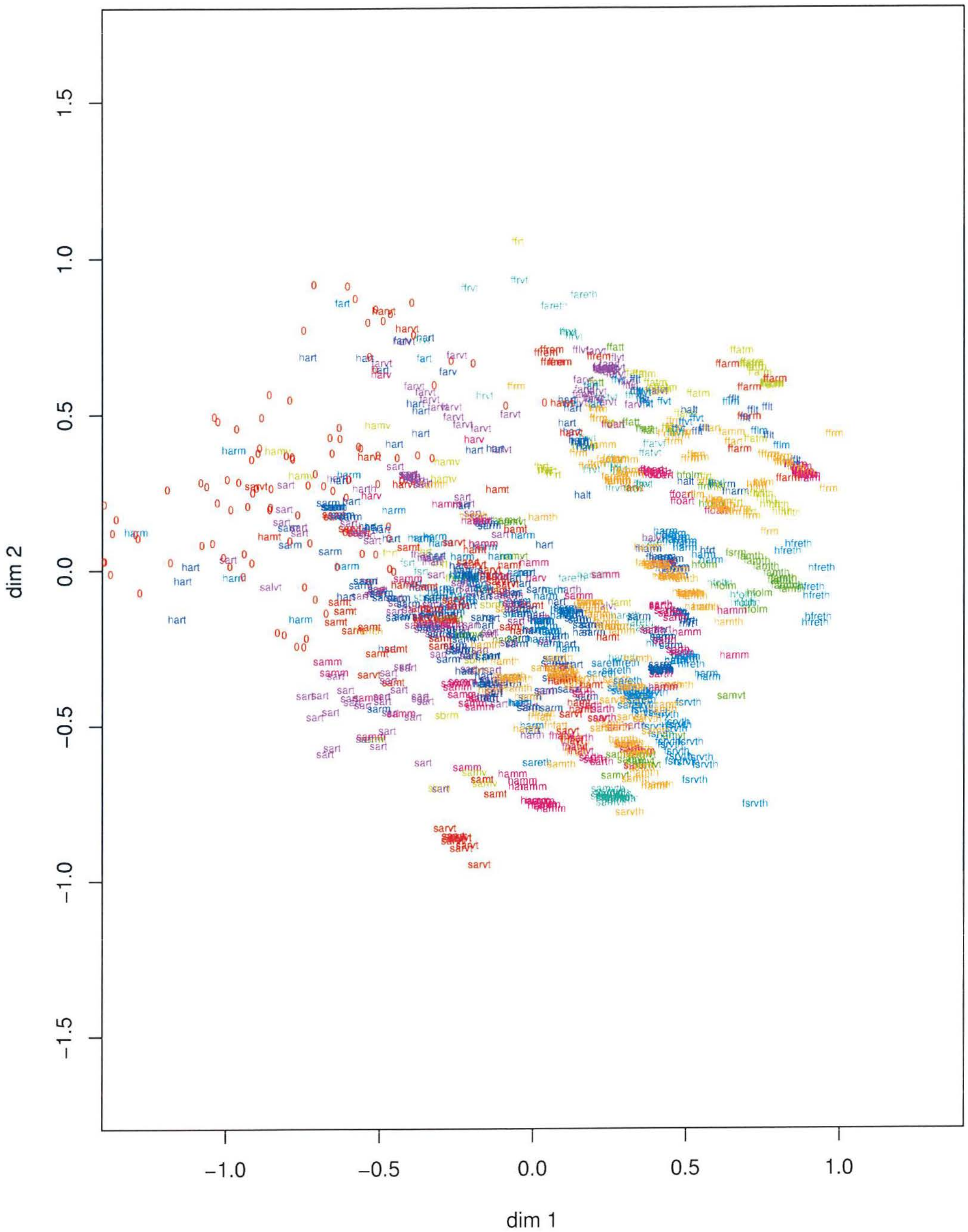

Figure 7.3

NMDS ordination plot of intrinsic soil characteristics as in Chapter 3 with individual soil pits labelled according to Australian Soil Classification for the order organosol to family level and the order tenosol, as defined in Table 7.2.

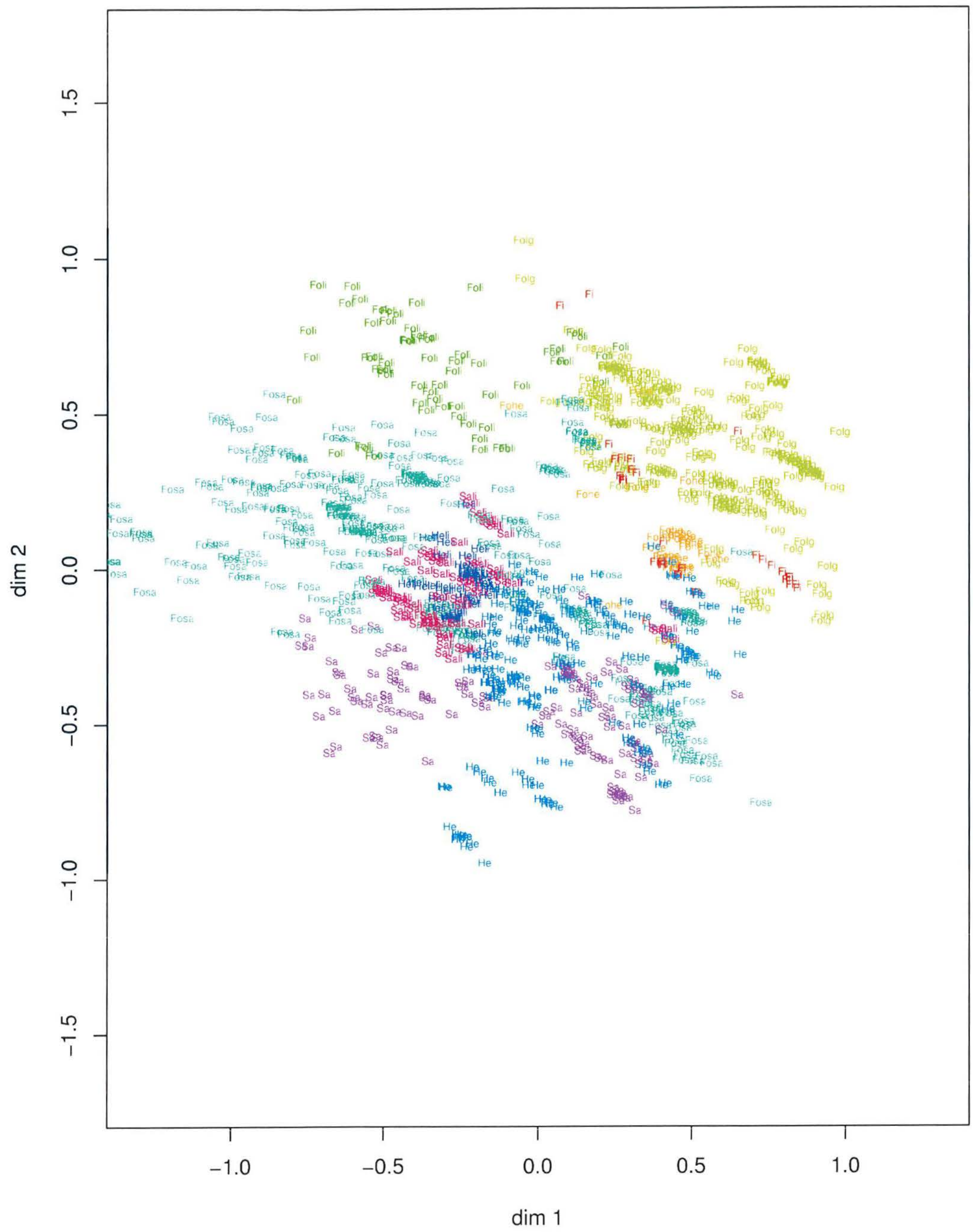

Figure 7.4

NMDS ordination plot of intrinsic soil characteristics as in Chapter 3 with individual soil pits labelled according to a revised Australian Soil Classification for the order organosol to great group level, as provided in Table 7.4.

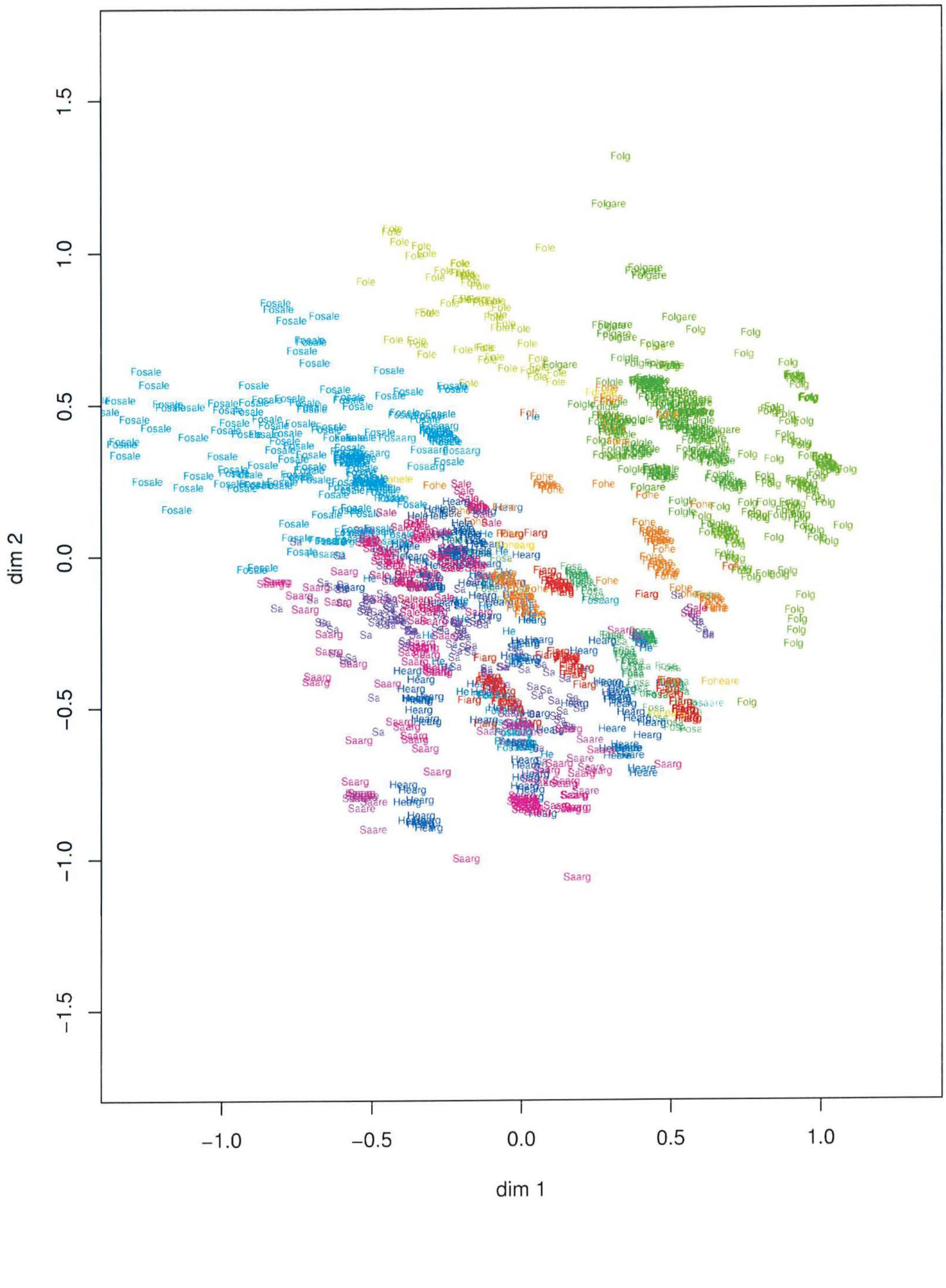

Figure 7.5

NMDS ordination plot of intrinsic soil characteristics as in Chapter 3 with individual soil pits labelled according to a revised Australian Soil Classification for the order organosol to sub group level, as provided in Table 7.4.

7.4 Discussion

7.4.1 Soil classification

The initial division in organic soils in the Soil Taxonomy, Canadian, English and Welsh classification systems is on the basis of the extent of waterlogging under which the organic accumulation occurs. This division divides folic soils which have formed under accumulating litter from soils that have formed under waterlogged conditions. In Tasmania, organic soils occur under waterlogged conditions, in depressions, river or lakesides or below springs, but most organic soils occur in aerated conditions in high rainfall areas. The shallow depths of the organic soils in Tasmania ensure that waterlogging does not occur in the sense described for soils in the northern hemisphere, although the low hydraulic conductivity of the moorland organic soils may produce layers of water saturated horizons and surface ponding. Therefore the initial division of folic and waterlogged organic soils is difficult to assess in the field. Both waterlogged and folic soils in Tasmania have dominant layers that can be fibric, hemic or sapric, although the present terms fibric, hemic and sapric are, in the Australian Soil Classification, and in other soil classification systems, intended to describe the humification characteristics of organic soil that has a water table near or at the surface for the major part of the year (Isbell 202).

The folic organic soils are found mostly on nutrient-poor sites in areas of high rainfall where soil development is limited to organic matter accumulation through the lack of mineral soil. There is no difference in nutrient status of ombrogenous and geogenous water supply, so the terms ombrotrophic and minerotrophic for sites on nutrient poor geology do not differentiate the organic soils. Folic organic soils can be fibric, hemic or sapric. They usually have a fibrous upper layer, grading through hemic to sapric with depth. With deep deposits, a sapric layer is present as the dominant horizon. Sapric horizons can also occur through both reducing and aerating conditions. Therefore the presence of a sapric horizon is not a reliable indication of the processes under which humification occurs. The occurrence of folic organic soils is strongly affected by the nature of the underlying substrate and the geology and vegetation type, as discussed in Chapters 4, 5 and 6. It was also shown in Chapters 5 and 6 that organic soils under succession from heath to forest experience an increase in organic carbon content and an increase in organic matter accumulation. The folic organic soils found under scrub, forest and rainforest have thicker fibric horizons, higher accumulation of nutrients and higher organic carbon content than the moorland soils.

To reflect the successional stages, it is suggested that the term lignic, defined in the WRB (FAO 2006), be used to differentiate sedge-dominated folic organic soils from woody-dominated folic organic soils. Folic organic soils also occur on Holocene sands where sands grade into organic folic material which may form an organic horizon of 5 cm to 2 metres. The degree of mixing of the folic organic materials and the underlying sand is variable and the term arenic, as defined in the WRB (FAO 2006), would be useful in describing these soils, rather than the more generic term, rudaceous.

The terms lithic, paralithic, terric and rudaceous were included in the Soil Taxonomy for engineering purposes (Brasfield 1984) and have no obvious value in differentiating organic soils in Tasmania. Organic soils found on a layer of transported, silty, weathered quartzite, commonly located at slope toes of along rivers, are covered using the term siltic, as defined in the WRB (FAO 2006). The nature of the underlying substrate, especially the nutrient status, would be descriptive, and, therefore, the terms argillic, arenic, siltic, and even siliceous would be informative, as well as identifiable on geology GIS layers.

The acidic and basic differentiae are of no practical use for Tasmanian organic soils as all fall under the definition of acidic. This term is useful for agriculture and forestry, but not for land under reservation. The more acidic organic soils occur under nutrient-poor geology, with the least acidic soils occurring over dolerite. A descriptor of geology would therefore be more informative than acidity, as rock type also influences nutrient status of the organic soils. Organic soils forming on dolerite are found on mineral soils, usually clays, in waterlogged conditions, such as depressions, river or lake inundation, associated with springs. The terms, argillic, as defined in the Australian Soil Classification (Isbell 2002), or clayic, as defined in WRB (FAO 2006), are suggested as potential labels for these organic soils.

7.4.2 The guiding principles of the Australian Soil Classification

The ability of the Australian Soil Classification to be used for mapping is one of the guiding principles in the revised edition (Isbell 2002). The importance of genesis was stressed in the design of Soil Taxonomy (Smith 1983). Here, the organic soil forming factors have been identified in order to predict and map Tasmanian organic soils. Using the current Australian Soil Classification can lead to a reasonable description of Tasmanian organic soils, but does not allow for mapping, even at the suborder scale, as the dominant defining characteristics of organic soils and organic soil accumulation in Tasmania are overlooked. Using internationally recognised differentiae, the Australian Soil Classification can be improved for describing Tasmanian organic soils, but mapping still requires a descriptive unit based on the characteristics of the soil, found through the dominant organic soil accumulating factors.

Another guiding principle, for the Australian Soil Classification, is that the primary land use and soil management should be the purpose of classification (Isbell 2002). In the case of organosols, the greatest areal extent is found under reservation where the dominant land management concerns are fire management and the maintenance of natural values (PWS 2004a). Fire management in organic soil regions should be able to make use of the organosol classification. Of particular use is the propensity of the organic soil to burn. This is related to the amount of carbon present and the aeration of the soil with folic, fibric organosols with a high organic carbon content more likely to burn than waterlogged, sapric organosols. Also related to fire is the length of time taken for the vegetation to succeed from buttongrass moorland, through scrub and wet eucalypt forest to rainforest, with succession taking less time on nutrient-rich sites, better-drained sites and sites with a reliable water supply. Sites with a shallow organic soil cover on nutrient-poor sites, sites with poor drainage and sites subject to drought will take longer to succeed.

As vegetation litter and root matter affect the nature and composition of the accumulating organic matter, it is important that these processes and characteristics are characterised in the classification. The supervised classification groups clusters according to organic carbon content, followed by humification, which allows for assessment of the soil types more likely to burn. Both the supervised and unsupervised classifications can be used in this manner, as the supervised clusters use vegetation and topography to describe the soils, which can then be related to both the susceptibility of the vegetation in a particular topographic position to fire as well as the organic soil type found under the vegetation. In order to identify natural values, the nature and extent of the soils in the reserved area, the nature of the processes dominating and affecting the soils and possible threats to the soils needs to be documented (PWS 2004a).

The reserved status of the land under which Tasmanian organic soils are found allows for the land to be used in a variety of ways, including for aesthetic appeal, tourism, scientific research, biodiversity, carbon accounting and intrinsic value, which gives a broad basis for the guiding principle of their classification.

One of the guiding principles of the Australian Soil Classification is that differentiae are compatible with international classifications. Organic carbon content, humification, total nitrogen content and depth were shown to adequately classify the unsupervised clusters in Chapter 4. Unfortunately, organic carbon content is not used as a differentiae in international and Australian soil classifications. Organic carbon content and organic soil depth were modelled in Chapter 6, and allowed the prediction of the extent and quantity of organic soils under certain broad vegetation types when limited by geology and climate. This analysis showed that, although buttongrass moorland organic soils are low in organic carbon content and mostly fall short of the internationally accepted definition of peatland, they cover an extensive area and contribute substantially to soil organic carbon stocks. The models also show managers the importance of making decisions concerning fire management, as encouraging organic soil accumulation is a complex issue. There is a requirement of signatory countries to produce a soil organic carbon stock under the Kyoto Protocol (UN 1997), and the Australian Greenhouse Office has produced several models for predicting soil organic carbon for agricultural land. It was assumed that the majority of soil organic carbon would be found under organosols on reserved land in Tasmania and that any new classification of organic soils should reflect the role of organic soils as a potential carbon sink, as well as identifying the extent of organosols.

7.4.3 Organic soil landform classifications

The major problem with classifying Tasmanian organic soils in terms of landform elements is that some of the major gradients used to describe and form the terminology of landform elements have their bases in *Sphagnum* peatlands. The terms that cause particular confusion are ombrogenous and ombrotrophic, used to describe the source of water supply and therefore the nutrient status of Northern Hemisphere peatlands. In Tasmania, it would be very difficult to assess whether some of the organic soils receive nutrients from an atmospheric or telluric source, as the ionic composition and nutrient content is similar (Buckney and Tyler 1976). The nutrient-poor quartzite and Holocene sands that form the majority of the west and south west organic soil-producing area are oligotrophic, but are rarely purely ombrogenous. The gradient therefore, of ombrotrophic to minerotrophic has no importance in Tasmanian organic soils. Based on the uncertainty, or irrelevance of the source of water supply from atmospheric or telluric sources, the term bog (as defined by Sjörs 1948, Malmer 1962, Fransson 1972, Tornocai 1998, Charman 2002, IMCG 2002), as a mire receiving exclusively ombrogenous water is also doubtful and the term blanket bog should probably not be used. The term fen (as defined by Sjörs 1948, Malmer 1962, Fransson 1972, Tornocai 1998, Charman 2002, IMCG 2002), as a mire which is influenced by water outside its own limits may be useful for some Tasmanian organic soils, where water of a higher nutrient status than the *in situ* substrate or rainwater is washed in, creating a different vegetation type than would otherwise exist. Otherwise the division between bog and fen in the sense of nutrient status of water which is not separable from the source of water is not helpful, as organic soils do not form on nutrient rich sites unless there is waterlogging through topographic position or continuous water supply from a spring or seepage.

The hydrogenetic classification (Succow 1998, Succow and Joosten 2001, Jensche and Succow 2004) could be applied to Tasmanian organic soil landscapes, although an agreement of what constitutes "peat" and "peatland" would need to be reached, as much of the extensive buttongrass plains are organic carbon poor, falling short of some set organic carbon content limits for "peat" and rarely reach depths of 30 cm over extensive areas, even on the floodplains. The necessity of some of the literature that "peat" be waterlogged (for example, Moore and Bellamy 1974) is also a problem as it ignores processes of organic soil accumulation other than a high water table.

The term 'mire' may also be problematic in that it requires waterlogging and therefore may not be an acceptable term for many areas of organic soils in Tasmania. The hydromorphological mire types would therefore only be applicable to organic soils that were obviously waterlogged and would not describe deeper, more organic-rich deposits under rainforest in a similar topographic position. As topographic position was found, in Chapters 5 and 6 to be important in describing organic soil accumulation and organic soil type, a landform classification that included topographic position would be useful. As the nutrient status of geology is important in determining whether a mineral soil or organic soil forms, the nutrient status of the underlying geology would also be useful. The vegetation provides the organic biomass, as well as affecting the hydrology of the system and would also be useful in providing additional detail to landform classification. As the hydromorphological mire types are based on the division of fen and bog, this cannot be used with confidence for Tasmanian organic soil landforms until a consensus is reached on the definitions of bog, fen and mire with respect to Tasmanian organic soils. It would not advisable to redefine, as this will no allow international correlation. Alternative suggestions for landform classification could be based on trophic status, topography or vegetation. Organic soils formed under high rainfall on nutrient poor geology do not currently have an adequate description and could be described as oligotrophic-geogenous. Topographic position could be used to describe organic soils as basin, valley, floodplain, sloping, saddle, crest flats or shelf. Geological nutrient status could be used to describe organic soils as oligotrophic or eutrophic. Vegetation under could be used to describe organic soils as sedge-moorland, *Sphagnum* moorland, Restiad-moorland, bolster moorland, alpine-sedgeland, rainforest, scrub, wet eucalypt forest, coastal rainforest, montane rainforest. The generic term peatland could be used, but using the definition of peatland meaning biotic landforms formed by organic rich soil, rather than peatland requiring waterlogging. The hydromorphological mire types work well for organic soils on nutrient rich sites with basin mire (fen), valley mires (fen), floodplain mires (fen) and sloping mires (fen) all found in the Central Plateau region of central Tasmania on dolerite. No true raised mires were found, although raised spring mires (fen) were found in the Central Plateau with nutrient-rich water upwelling in the centre of the mire, the largest found in the Walls of Jerusalem.

7.5 Conclusion

Tasmanian organic soils are undoubtedly distinctive in the floristic composition of the vegetation that forms them and in the characteristics and gradients that describe them. These soils and landforms do not readily fit into international classification systems. In attempting to achieve equivalence, compromises are made that do not accurately characterise the true nature of the soils. A more representative description is obtained through the supervised clustering produced in Chapter 5 and the organic carbon modelling produced in Chapter 6 which both describe the geographic setting under which organic soils occur and the dominant organic soil accumulating processes. The typifying characteristics found in the unsupervised clusters are then more clearly defined and understood once the location and extent of the organic soils are ascertained. It is expected that further work and classification to family level in the Australian Soil Classification and finer scale resolution mapping will be possible, especially as more detailed vegetation, geology and DEM maps become available.

Chapter 8

Management Issues

8.1 Introduction

Organic soils occur predominantly on reserved land in Tasmania. The reserved land comprises national parks, state reserves and the world heritage area. Management focuses on criteria forming selection criteria for world heritage area selection and designation outlined in Chapter 1. Management of areas containing organic soils, organic soil landforms and processes, therefore, is primarily concerned with conservation for biodiversity, geodiversity, scenic values and cultural values.

8.2 Geodiversity

Management issues relevant to findings in this thesis are primarily concerned with geodiversity. Geodiversity has been defined as, 'the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, physical processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems' (Gray 2004). The definition of geodiversity used in the Tasmanian World Heritage Area (PWS 2004a) is, 'the natural range of geological (bedrock), geomorphological (landform), and soil features, assemblages, systems and processes. Geodiversity includes evidence for the history of the earth (evidence of past life, ecosystems and environments) and a range of processes (biological, hydrological and atmospheric) currently active on rocks, landforms and soils' (PWS 2004a). It has been argued that the earth's biodiversity is largely due to its geodiversity and that for land management to be fully effective, a holistic understanding and approach is needed (Gray 2004). It is therefore necessary to identify the specific geodiversity values associated with organic soils and the potential threats to those before appropriate management can be identified.

8.3 Geodiversity values

The geodiversity values of organic soils are the soil groups, landforms associated with organic soils and the organic soil-forming processes. The values associated with organic soils are, according to Gray (2004): intrinsic; cultural; aesthetic; economic; functional; and research and educational.

The intrinsic value should be recognised, not just of organosols and the variety of organic soil groups, but also the specific landform features found on organic soils, such as wetlands and peat mounds. Tasmanian organic soil-forming processes also have outstanding intrinsic value. The organic soils, soil-forming processes and soil landforms are all exceptional on a global scale.

The cultural value of the Tasmanian organic soils, associated landforms and soil-forming processes are closely linked with the continuous occupation and repeated burning of the landscape by Aborigines until the mid-nineteenth century. Buttongrass, the vegetation under which the greatest areal extent of organosols are found, is frequently ignited through lightning strikes, although the literature has, in the past, stated that their incidence was low (Jackson and Bowman 1982, Ingles 1985). Improved monitoring techniques and modelling has shown that the current pattern of buttongrass moorland throughout Tasmania would be similar with lightning strikes alone (King *et al.* 2006). However, the ideal buttongrass pattern for biodiversity values and fire hazard fuel reduction has been attributed to repeated Aboriginal burning throughout the west and southwest for route creation and game control over the last 22,000 - 34,000 years (Jarman and Brown 1983, Cosgrove 1995, Marsden-Smedley 1998). It was thought that buttongrass moorland was maintained before white mineral discoveries in the 19th century (Jackson 1999), by frequent, low intensity, small-scale burning used by Aboriginal fire-stick burning and large-scale, infrequent high-intensity wild fires after 1850 (Marsden-Smedley 1998). Low altitude coastal buttongrass plains in the west and south west of Tasmania cover the full range of topographic locations on nutrient-poor parent material and it was thought that Aborigines maintained these moorlands through repeated burning of these areas (Marsden-Smedley 1998).

The aesthetic values and cultural values are closely linked with the process of vegetation succession following fire in lowland areas, as described in Chapter 1. Vegetation succession following fire is dependent on the underlying substrate, thus creating a highly diverse landscape which is aesthetically appealing to visitors.

Economic values must be associated with aesthetic values and the appeal of the landscape for recreation and tourism. All forms of peat-mining, soil collection, *Sphagnum* harvesting cannot be assessed to be sustainable, as there are little data on organic soil accumulation rates. What has been published (see Chapter 2) suggests that harvesting would not be sustainable (Whinam and Buxton 1997).

Tasmanian organic soils may provide a variety of functional values. Tasmanian organic soils store and recycle carbon. More research is required to ascertain the extent to which the specific organic soil groups are sequestering or releasing carbon. The present soil organic carbon stores (Chapter 6) are spatially highly variable. Fortunately, the soil organic carbon stores are strongly correlated with certain environmental factors and can therefore be predicted and mapped. Organic soils would be expected to play a role in the hydrological function of a catchment by storing, filtering and releasing water. Tasmanian organic soils provide a diverse environment, habitat and substrate which create and nurture biological diversity. Organic soil-forming processes provide a medium for a build-up of nutrients allowing for vegetation succession processes to be accelerated. A mosaic of organic soil types provide a diverse habitat and therefore biodiversity. An example of the creation of organic soils as a habitat is the provision of a medium and environment for the freshwater burrowing crayfish (see Plate 8.1).

Plate 8.1

Freshwater burrowing crayfish positioned beside its recent excavations for trapping water. The image was taken a few days following an ecosystem management burn.

Tasmanian organic soils provide a range of scientific and educational values. Palynological research outlined in Chapter 2 has used pollen records held in organic soils and organic soil constituents to reconstruct the history of Aboriginal occupation, burning, and climate change. For example, palynological research shows the dominance of buttongrass moorland during the Holocene throughout the south west region (Thomas 1993, Macphail *et al.* 1993, Fletcher 2000, Tye 2002, Fletcher and Thomas 2007). Palaeosols have been used to reconstruct past climates and vegetation (Macphail *et al.* 1995) and peat accumulation rates have been inferred through carbon-dating of organic soils (Macphail *et al.* 1999). Organic soils provide a rich educational and training opportunity for the sciences.

8.4 Threats to geodiversity

The majority of organic soils occur under reserved land and therefore the current threats to organic soils in Tasmania are likely to arise through visitor use impacts and land management practices, particularly burning. The PWS (2004a) identified the main potential impact on geodiversity to be soil erosion.

8.4.1 Threats from fire

Grazing and burning-induced sheet erosion processes over the last two centuries on the Central Plateau (Cullen 1995) have been reported to have degraded 10,000 ha, which would have, most probably, included organic soils. An estimated 34,000 ha of the Birches Inlet area in the south west of Tasmania has been reported to have been eroded with a total of 100,000 ha of buttongrass moorland soils degraded through peat loss caused by fire (Pemberton 1988, 1989), although the lack of soil cover on these slopes has most likely been a long term feature, as historical records show these areas were bare by 1833 (Marsden-Smedley 1998). Whether the observed bare slopes are a result of Aboriginal, lightning or white settler initiated burning, present-day management aims to avoid burning on slopes (PWS 2004b). Despite the recommendation, many slopes are routinely prescribed burned.

The effects of fire on upland areas can be devastating. In the late 19th and early 20th centuries, certain presently reserved areas of the west, southwest and central highlands of Tasmania where organic soils are found were burned, and small areas used for grazing and mineral exploration (Jackson 1999). Upland vegetation is particularly fire sensitive (Kirkpatrick and Dickinson 1984a), but the effect of fire in upland organic soils is not uniform. In Tasmanian upland areas, organosols are shallow where fire frequency is high. Organosols under fire-sensitive *Athrotaxis* species are deeper and have a more fibrous and organic carbon rich content than organosols found under vegetation on well-drained sites on the identical substrate that has experienced more frequent burning. For *Athrotaxis*-dominated vegetation types, replication is difficult due to the reduction of former areas of the upland pine forest through burning (Harris and Kitchener 2005). The loss of nitrogen through burning and subsequent leaching was observed by Kirkpatrick and Dickinson

(1984a). As the better-drained sites are aerated and fibrous, they are therefore susceptible to fire, oxidation and subsequent mechanical erosion. On nutrient-poor geology, where productivity is lower and recovery from fire a slow process, deep, organic rich and fibrous soils are rare. Waterlogged sites occurring, for example, next to tarns or corries, and bolster heath dammed waterways, have humified, shallow and organic rich organosols whether they have been frequently burned or not.

The effect of fire on lowland organic soils is also variable. Lower altitude vegetation is routinely burned to protect fire-sensitive alpine vegetation, remnant pine forest and rainforest. Buttongrass moorlands are highly pyrogenic and the species found within them, especially *Gymnoschoenus sphaerocephalus* and Restionaceae species, accumulate dead biomass which provides fuel and burns under relatively wet conditions (Marsden-Smedley 1998). Jackson (1968) provided a model of vegetation succession in which lowland Tasmanian fire frequency was posited to control changes from a highly pyrogenic, frequently burned buttongrass moorland through scrub, wet eucalypt forest to rainforest as the climax community with infrequent burning (Jackson 1968, Kirkpatrick 1977b, Jarman and Brown 1983), described in Chapter 1. The succession is swift on high nutrient sites and slow on low nutrient sites (Jackson 1968). The succession from buttongrass to rainforest on nutrient-rich geology often results in a succession from organosols to a mineral soil with a peaty or a humose horizon. The loss of nitrogen is consistent with findings on nitrogen loss through fire and subsequent leaching both in England (Allen 1964) and in moorland soils in Tasmania (Jackson 1968, Harwood and Jackson 1965). The reduced organic content was also found by Pemberton (1988, 1989) for organic soils under buttongrass moorland on slopes and across fire boundaries.

Increased waterlogging of valleys and flats through burning has been well documented in Europe (Charman 2002, Succow and Joosten 2001). The removal of slope forests and subsequent increased run-off and waterlogging of valleys and flats may serve to slow down the succession from buttongrass to scrub where poor drainage is maintained with the higher frequency of burning experienced in the more flammable buttongrass. These lowland organosols are highly variable in organic carbon content and soil depth, with the variation depending on topography. Deeper soils are found in depressions and periglacial outwash channels. Shallower, less organic soils are found in well-drained and frequently burned areas on slopes and onperiglacial outwash features, such as braided bars.

8.4.2 Threats from visitor impact

Threats to organic soils from visitor impact are predominantly through the effect of trampling. Whinam and Chilcott (2003) have quantified the loss of vegetation cover and organic soils to walker impact on alpine organic soils on quartzite in the Western Arthur Range. The western alpine vegetation types were found to be sensitive to trampling with 30-100 passes resulting in a vegetation recovery only after 2 years. Flat alpine sites, with a high water table, experienced vegetation destruction at 200 passes, resulting in an organic soil structure change through poaching. Poached alpine soils on sloping sites were observed to be removed and deposited downslope. At 200 passes there was no visible recovery 2 years after the experiment (Whinam and Chilcott 2003). Similar results have been observed on alpine and rainforest organic soils on Mt. Sprent and Mt. Murchison (pers. obs.) and in bolster heath communities (Gibson 1984). Five permanent markers on Mt. Murchison show between a 25 to 50 cm loss of organic soil in rainforest and subalpine vegetation. The notable difference between the Western Arthur sites (Whinam and Chilcott 2003) and the Mt. Murchison site, is that the Mt. Murchison site has no permanent water table and is therefore not waterlogged. The walker impact on Mt. Murchison has removed the vegetation and fine roots and pulverised the organic soil through the removal of the fine root system (see Plates 8.2 and 8.3).

Plate 8.2

An over-deepened track on sub-alpine organic soil on a steep section of Mt. Murchison, western Tasmania. The track has eroded around 25 cm over the last 2 years at this particular section.

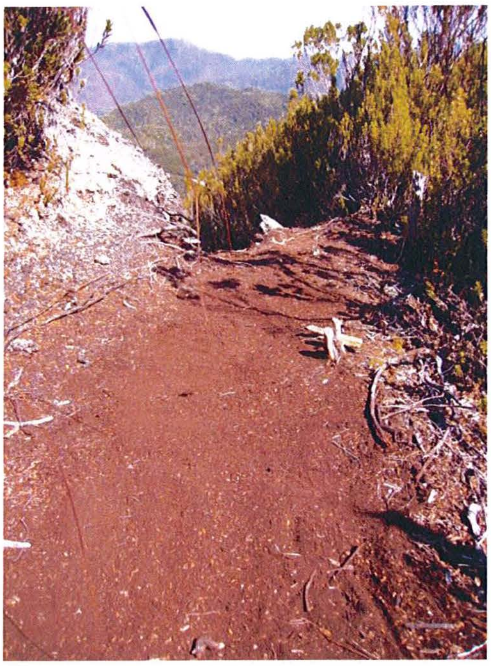

Plate 8.3

A flatter section around 20 m from Plate on a sub-alpine organic soil on Mt.Murchison, western Tasmania. Notice the pulverised organic soil on the track.

8.5 Geoconservation

In Tasmania, geoconservation has been defined as, 'the conservation of geodiversity for its intrinsic, ecological and (geo)heritage values' (Sharples 2002), and as, 'the identification and conservation of geological, geomorphological and soil features, assemblages, systems and processes (geodiversity) for their intrinsic, ecological or heritage values' (Eberhard 1997). Geoheritage has been defined as, 'those particular examples or elements of natural geodiversity which are of significant value to humans for non-depleting purposes which do not decrease their intrinsic or ecological values' (Sharples 2002), and as, 'those components of geodiversity that are important to humans for purposes other than resource exploitation; things we would wish to retain for present and future generations' (Eberhard 1997). In addition, Sharples (2002) identifies two main aims of geoconservation: to retain significant representative examples of the (geo)diversity of bedrock, landform and soil features; and, to maintain natural rates of magnitude and change. Geoconservation measures in Tasmania have focused on geoheritage for which sufficient geodiversity data which has been collected, for example, karst features (Eberhart 1994, 1996), fluvial (Jerie *et al.* 2001), coastal features (Sharples 2002) and glacial features (Kiernan 1996, 1997).

The recognition of the conservation value of organic soils in Tasmania has been realised in the criteria for listing in the World Heritage Area (DPWH 1992), detailed also in Chapter 1. The Tasmanian Wilderness World Heritage Area Management Plan (TWWHAMP) (PWS 1999) sets out management objectives, management prescriptions, key desired outcomes and monitoring and evaluation for the conservation of geodiversity. Monitoring and evaluation actions in the TWWHAMP (PWS 1999) cover organosol erosion and the effects of fire on organosols. The Department of Primary Industries and Water (DPIW) also maintain an inventory of 69 soil sites that are recognised as having geoconservation value in the Tasmanian Geoconservation Database (TGD). Both the TWWHAMP and the TGD geoconservation database of organic soils refer to the 'extensive blanket peat bogs' of western Tasmania, a term found, in this thesis, to be inappropriate for the organic soils found in this region. It is vitally important for adequate conservation measures to be put in place, that there is no inappropriate use of borrowed labels from northern hemisphere peatland ecology. Terminology which infers processes that have been shown, in this thesis, not to be relevant in Tasmania, should not be loosely applied to Tasmanian organic soils. It is not clear whether the nomenclature in the database is referring to a presumed potential soil cover or a present-day assumption of soil cover. Either way, the carbon contents, soil depths and soil-forming processes do not match the internationally accepted definition of blanket bog (see Chapter 2 and Chapter 7). As the TGD is a map-based database and informs the TWWHAMP, it may be more useful to use the supervised clusters to describe the diversity, spatial extent and rarity of organic soils and organic soil landforms. A number of representative soil sites can be identified which could be used to provide data for the TGD yearly updates of the database which contain information on both site and process integrity, with data on the condition (degradation) and conservation status and global significance of organic soil geodiversity in Tasmania.

Site integrity regarding organic soils and organic soil landforms refers to, "...the maintenance of the forms of significant landforms, or the maintenance of the profiles and coverage of soils at significant representative soil sites" (Sharples 2002). Process integrity refers to, "...the maintenance of the relevant natural processes operating in or upon a site or system of geoconservation value" (Sharples 2002). The processes of organic soil development on buttongrass moorland, scrub, wet eucalypt forest and rainforest on nutrient-poor geology are especially worthy of geoconservation recognition in Tasmania due to their relationships with succession of the vegetation following fire. The succession through buttongrass, scrub, wet eucalypt forest to rainforest on a nutrient-poor substrate results in a globally rare organic soil type which deserves a high level of conservation. The vulnerability of the rainforest organic soils to fire is high due to their low moisture content, low bulk density, topographic position and high organic content. The vulnerability to destruction from fire and the low productivity of alpine organic soils on nutrient-poor geology also warrants high conservation status for this soil type. Landform features, such as peat mounds forming on gravel rises on sandar, also deserve a high conservation status due to the possibility of drying out and destruction through wildfire. Alpine and montane organic soils on nutrient-rich substrates should also be considered for geoconservation status. *Sphagnum* and sedge-dominated springs and flushes, and *Sphagnum*-dominated deep depressions cover a small area, but contain a large amount of carbon. The nutrient-rich alpine organic soils are geogenic water-input dependent and a change in local hydrological conditions would have a severe effect on their existence. Work has been done on the conservation of *Sphagnum* communities, although the studies contain no organic soil data (Whinam *et al.* 2001).

There have been no quantitative measures set in place for organic soil conservation, with no studies published on the effect of fire and wildfire on a cross-section of organic soil types in a variety of topographic positions. Despite the lack of data, fire management in the reserved areas has considered the potential for 'peat fires' (see Marsden-Smedley *et al.* 1999). Fire management for nature conservation in Tasmania has focused heavily on the management of certain vegetation types and habitats (ecosystem management burning) as well as hazard reduction burning (see PWS 2004b). Current fire management in reserved areas of Tasmania includes wildfire suppression, biodiversity burns and fuel hazard reduction burns. At present, priority in management is given to the reduction of wildfire occurrence through fuel reduction of lowland vegetation adjacent to upland, fire-sensitive vegetation and adjacent rainforest. There is an obvious need for balance between hazard reduction burning to suppress fuel loads which could spread to sensitive areas in a wildfire and limiting frequent burns on convex slopes which are prone to drying out and have a low productivity rate on nutrient-poor substrate. Visitor-initiated wildfires have been reduced through the introduction and enforcement of fuel-stove only camping and hazard-reduction burning along roads. Ecosystem management burns are given third priority in management of the world heritage area, and regard is given to the potential impact of burning on organic soils with the advice to avoid burning on mappable slopes $\leq 15^\circ$, and, if possible, $\leq 10^\circ$ (PWS 2004b). Ecological management burn plans also prescribe the retention of a layer of thatch on the ground and the extinguishment of burning peat, logs and boundaries.

In order to focus geoconservation management priorities, an assessment of the sensitivity of the organic soils to the identified threats to geodiversity outlined above should be developed. A 10-point geosensitivity scale has been developed in Tasmania for sensitive features (Kiernan 1997, Sharples 2002). Highly sensitive features have been assigned a more protective management response than features sensitive to only catastrophic events. A similar scale could be developed for organic soil types, associated landforms and processes, focusing on the major threats of the effects of fire management and trampling.

8.6 Conclusion

For adequate conservation of organic soils, their values need to be identified, agreed upon and intimated to land managers. Threats to the identified values require quantification, where feasible. The vulnerability, sensitivity and rarity of organic soil types also need to be assessed for successful management. There is much work to be done.

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Appendix 1

Table 1

Soil variables, codes and units of measurement used in data analysis.

code	*definition*
orgA	organic matter in the top horizon, if present. Expressed as percent of total sample weight
orgB	organic matter in the lower horizon, if present. Expressed as percent of total sample weight.
CA	organic carbon content in the top horizon. Expressed as percent of total sample weight.
CB	organic carbon in the lower horizon. Expressed as percent of total sample weight.
DepthA	depth of the top horizon. Expressed in metres.
DepthB	depth of the lower horizon, if present. Expressed in metres.
TotDepth	total depth of soil. Expressed in metres.
WT	drainage of soil profile. Assigned to a class of 1-6.
BDA	bulk density of the top horizon.
BDB	bulk density of the lower horizon, if present.
DrainageA	drainage class of top horizon. Assigned to a class of 1-6.
DrainageB	drainage class of top horizon, if present. Assigned to a class of 1-6.
HumA	humification of the top horizon. Expressed on an ordinal class scale of 1-10.

HumB	humification of the lower horizon, if present. Expressed on an ordinal class scale of 1-10.
pHA	pH of the top horizon. Expressed in pH units.
pHB	pH of the lower horizon, if present. Expressed in pH units.
NitA	Total nitrogen of the top horizon. Expressed as percent of total sample weight.
NitB	Total nitrogen of the lower horizon, if present. Expressed as percent of total sample weight.
CarbA	Total organic carbon of the top horizon. Expressed as percent of total sample weight.
CarbB	Total organic carbon of the lower horizon, if present. Expressed as percent of total sample weight.
ChromaA	Colour – chroma of the top horizon. Munsell chroma.
ChromaB	Colour – chroma of the lower horizon, if present. Munsell chroma.
Horiz	Total number of horizons noted (not counting a C horizon).

Appendix 2

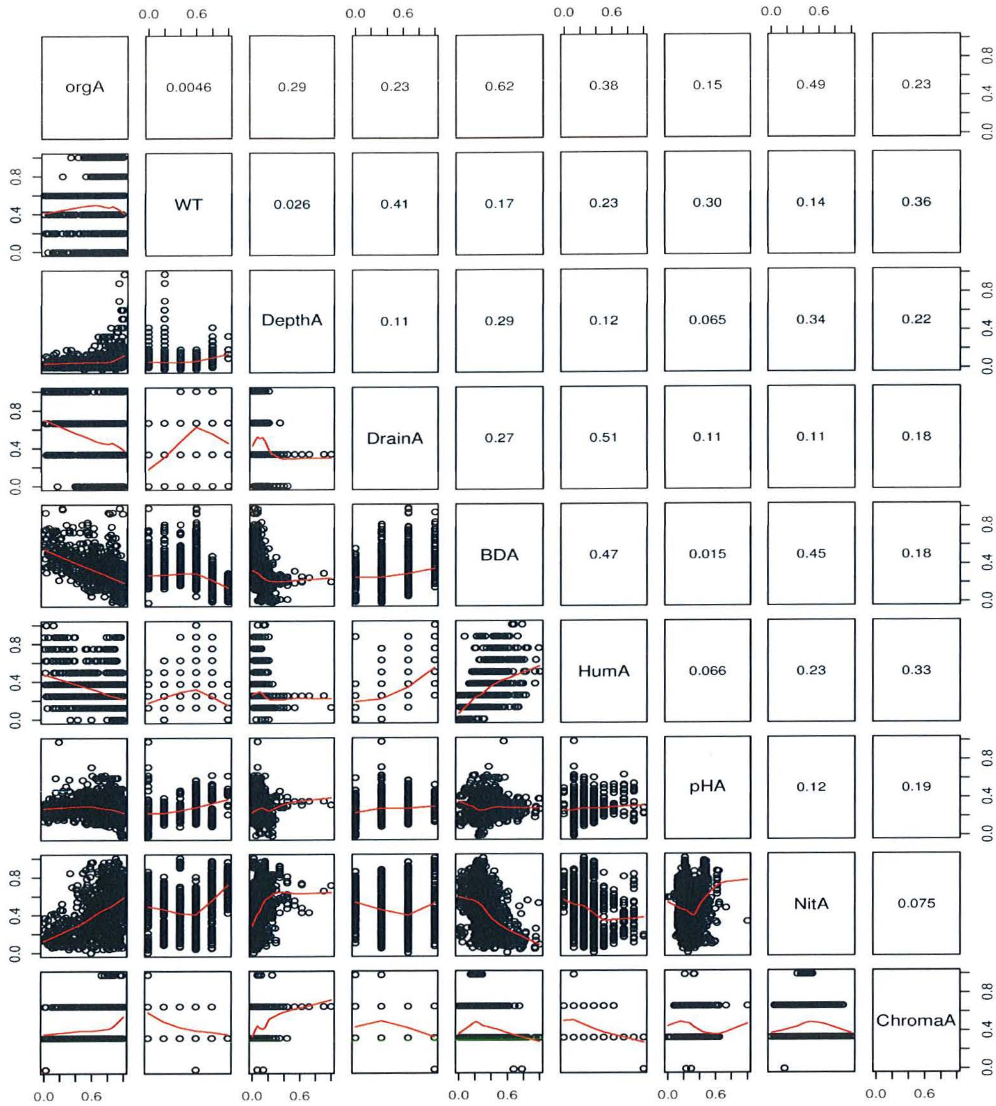

Figure 1

Pairs plot of intrinsic soil characteristics. Plot codes given in Appendix 1 and described in Chapter 3 Methods. Spearman's rank correlation co-efficient provided in the upper plot area.

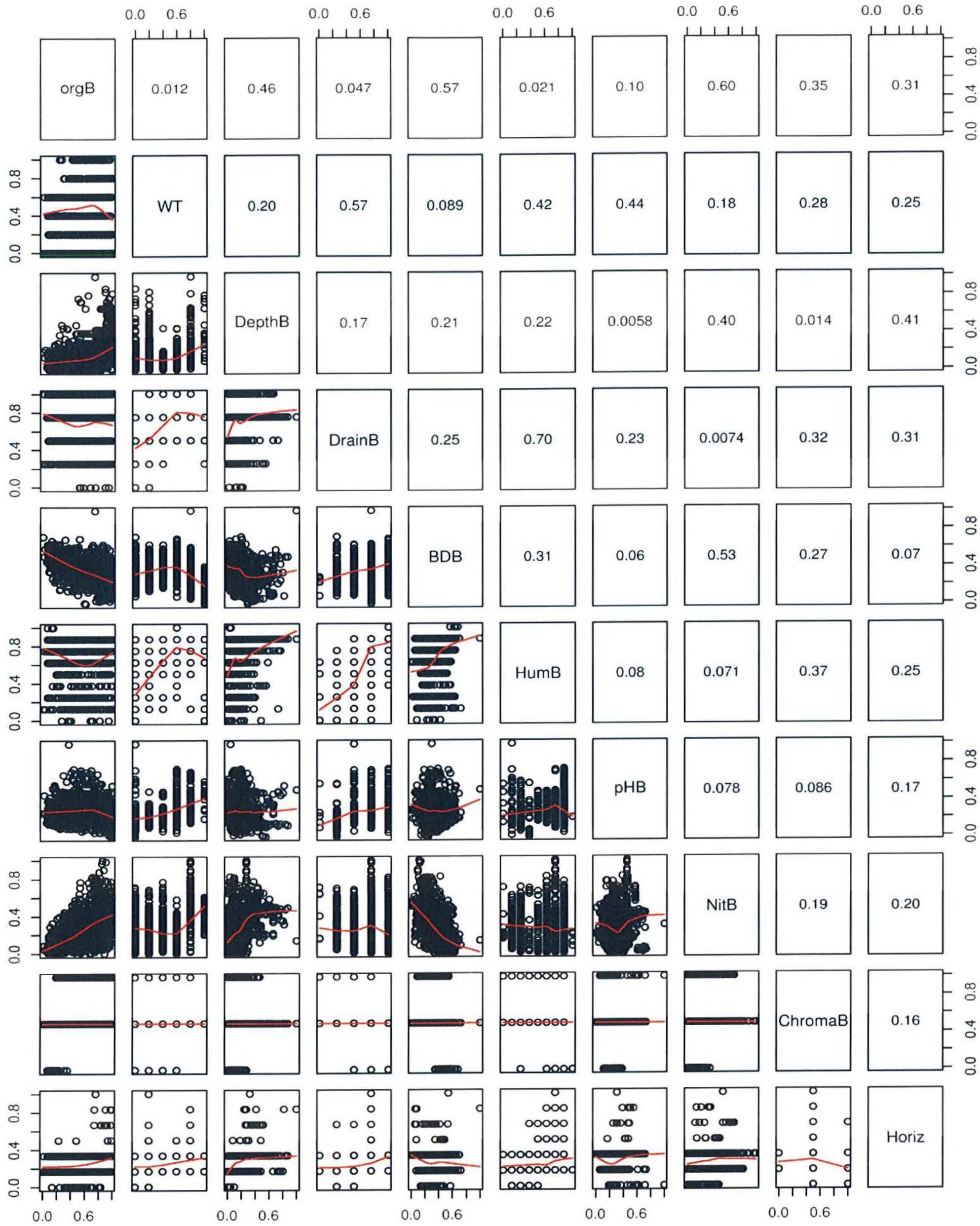

Figure 2

Pairs plot of intrinsic soil characteristics. Plot codes given in Appendix 1 and described in Chapter 3 Methods. Spearman's rank correlation co-efficient provided in the upper plot area.

Appendix 3

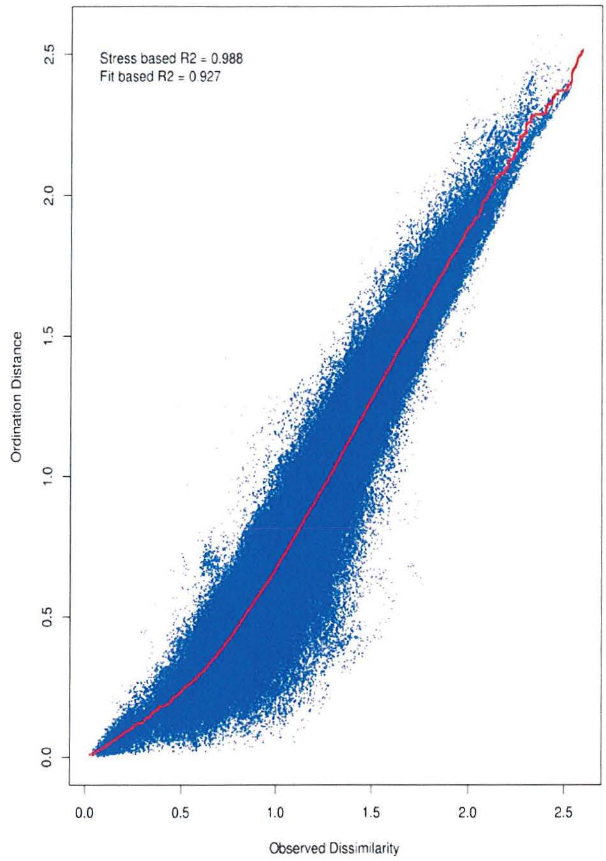

Figure 1

Stress plot of the non-metric multidimensional scaling ordination. The x axis represents the observed dissimilarity given by the dissimilarity matrix and the y axis represents the ordination dissimilarity. The correlation is high, at 97%.

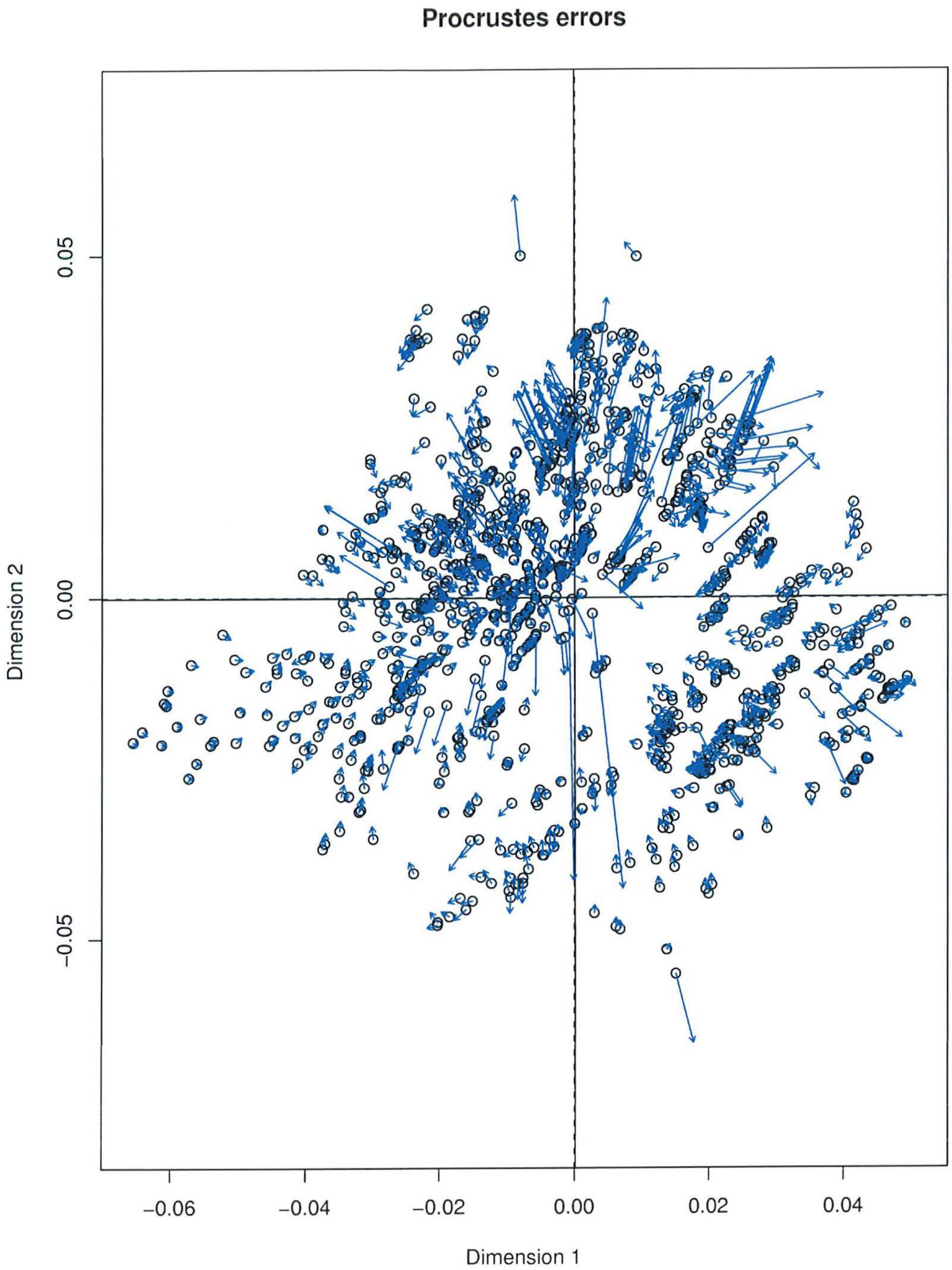

Figure 2

Procrustes rotation on the non-metric multidimensional scaling ordination in 2 and 3 dimensions shows the movement of points on the 2 dimensional ordination plot.

Appendix 4

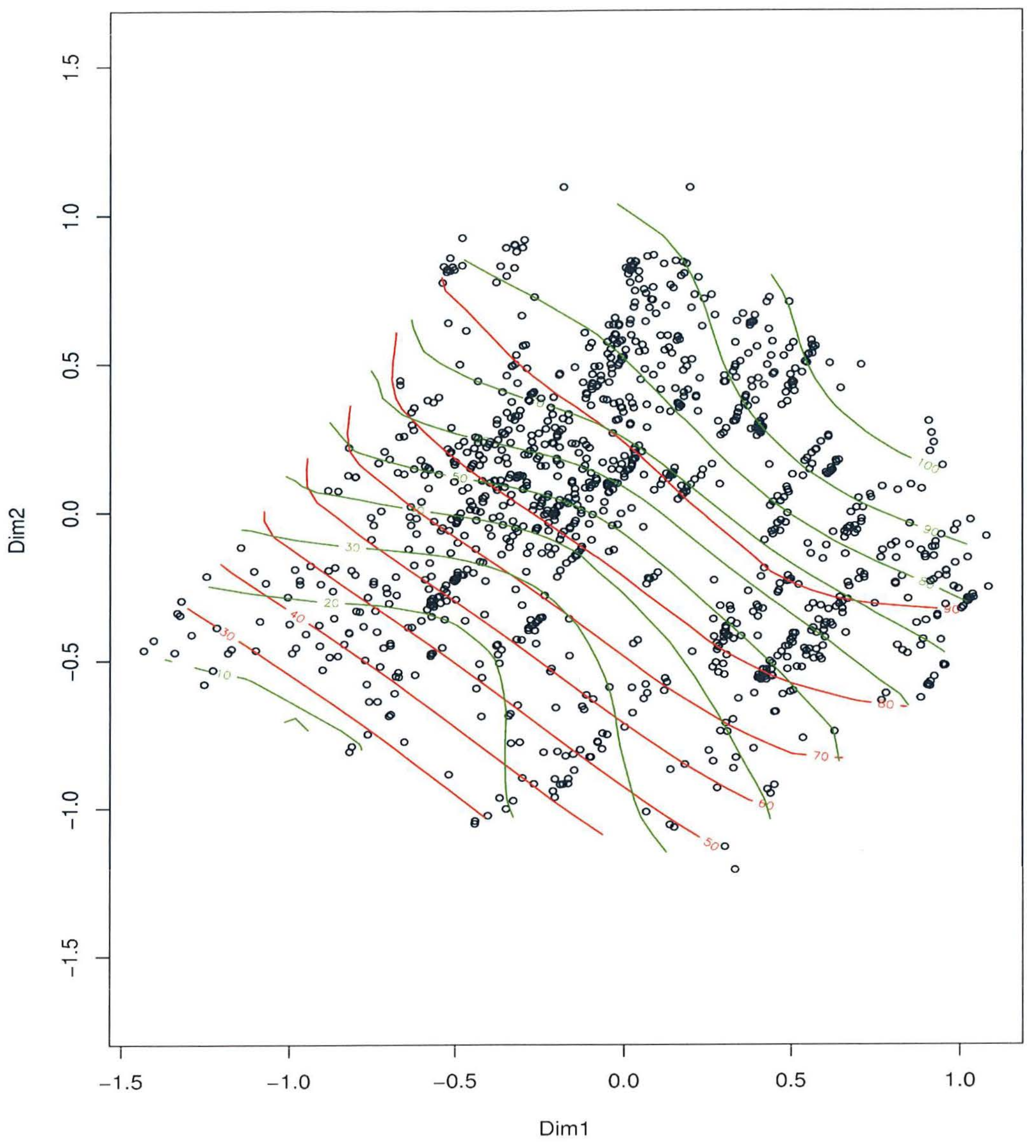

Figure 1

Thinplate spline smoothing contours overlay on ordination plot. Red lines show organic carbon content for the upper horizon and green lines show the organic carbon content (multiplied by a factor of two) for the lower horizons.

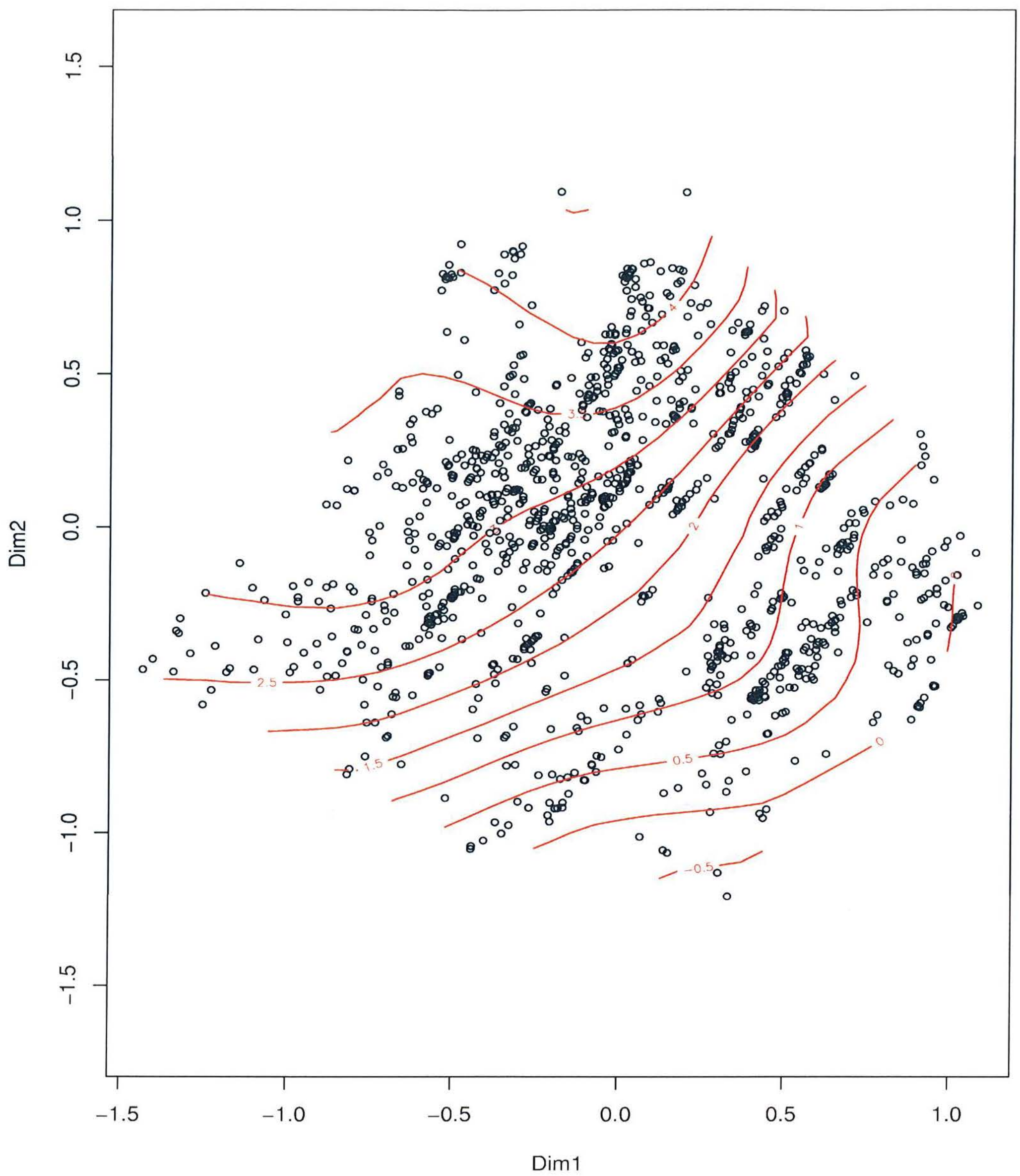

Figure 2

Thinplate spline smoothing contours overlay on ordination plot. Red lines show the water table classes.

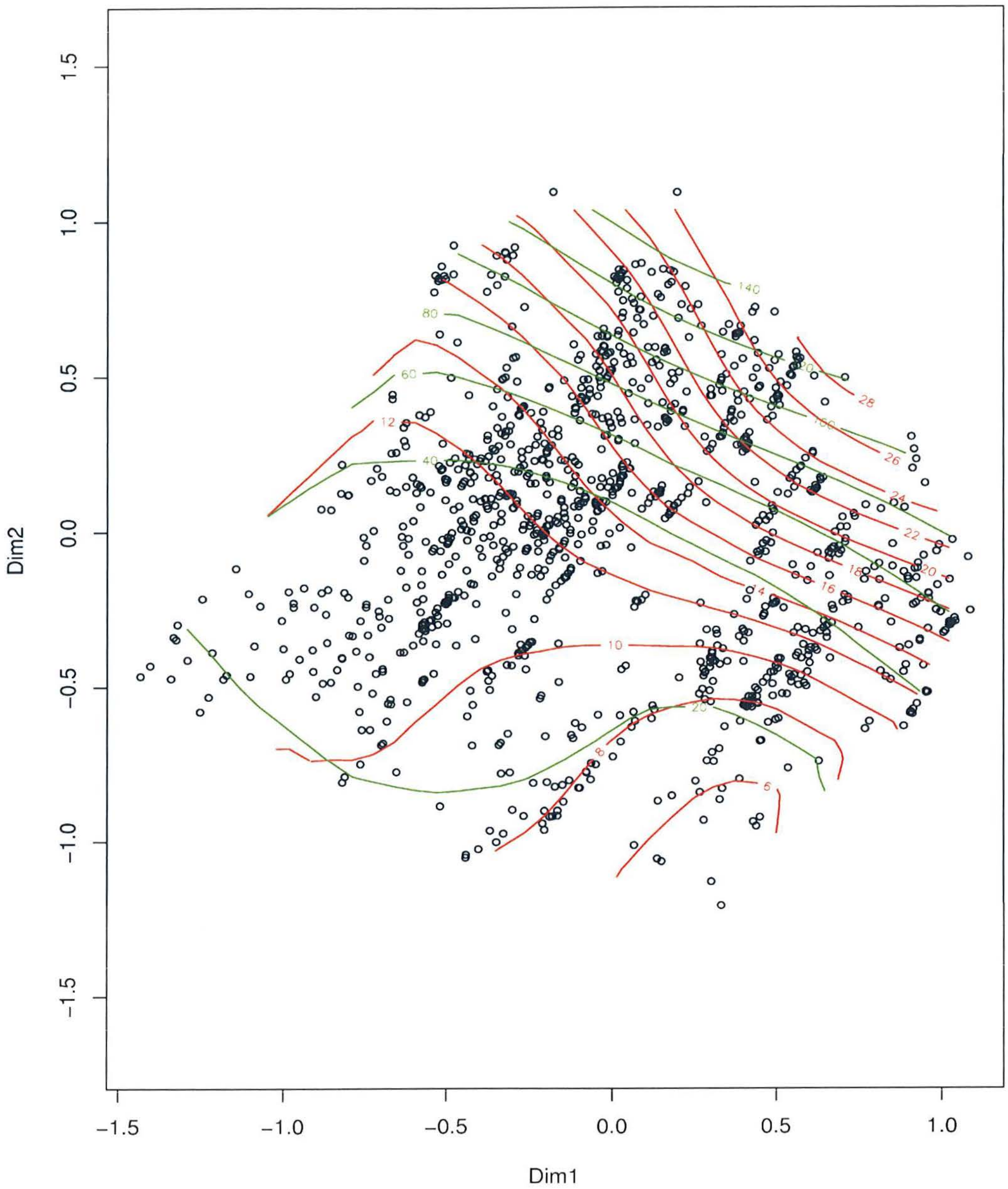

Figure 3

Thinplate spline smoothing contours overlay on ordination plot. Red lines show soil depth in centimetres for the upper horizon and green lines show soil depth in centimetres for the lower horizons.

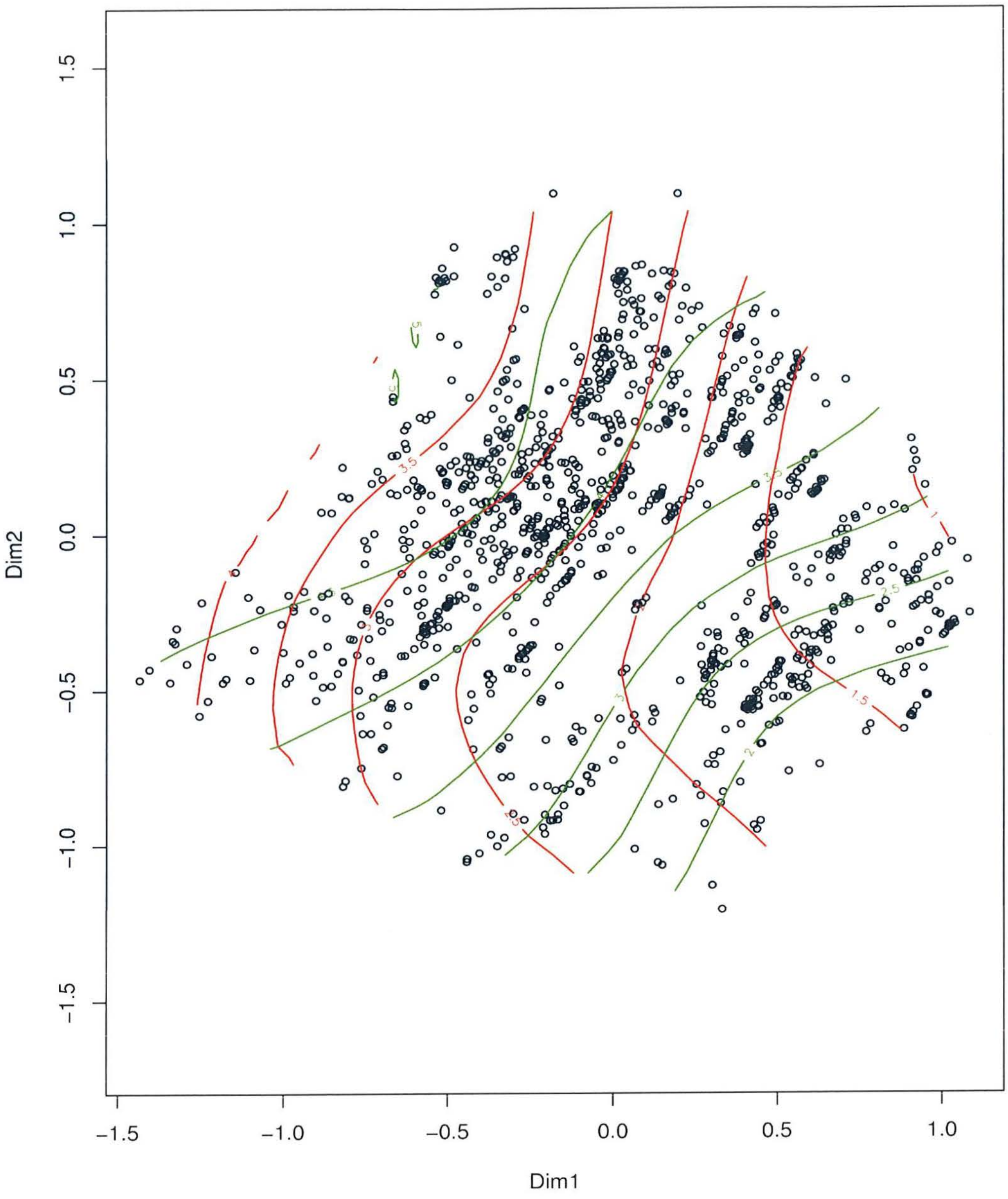

Figure 4

Thinplate spline smoothing contours overlay on ordination plot. Red lines show drainage classes for the upper horizon and green lines show drainage classes for the lower horizons.

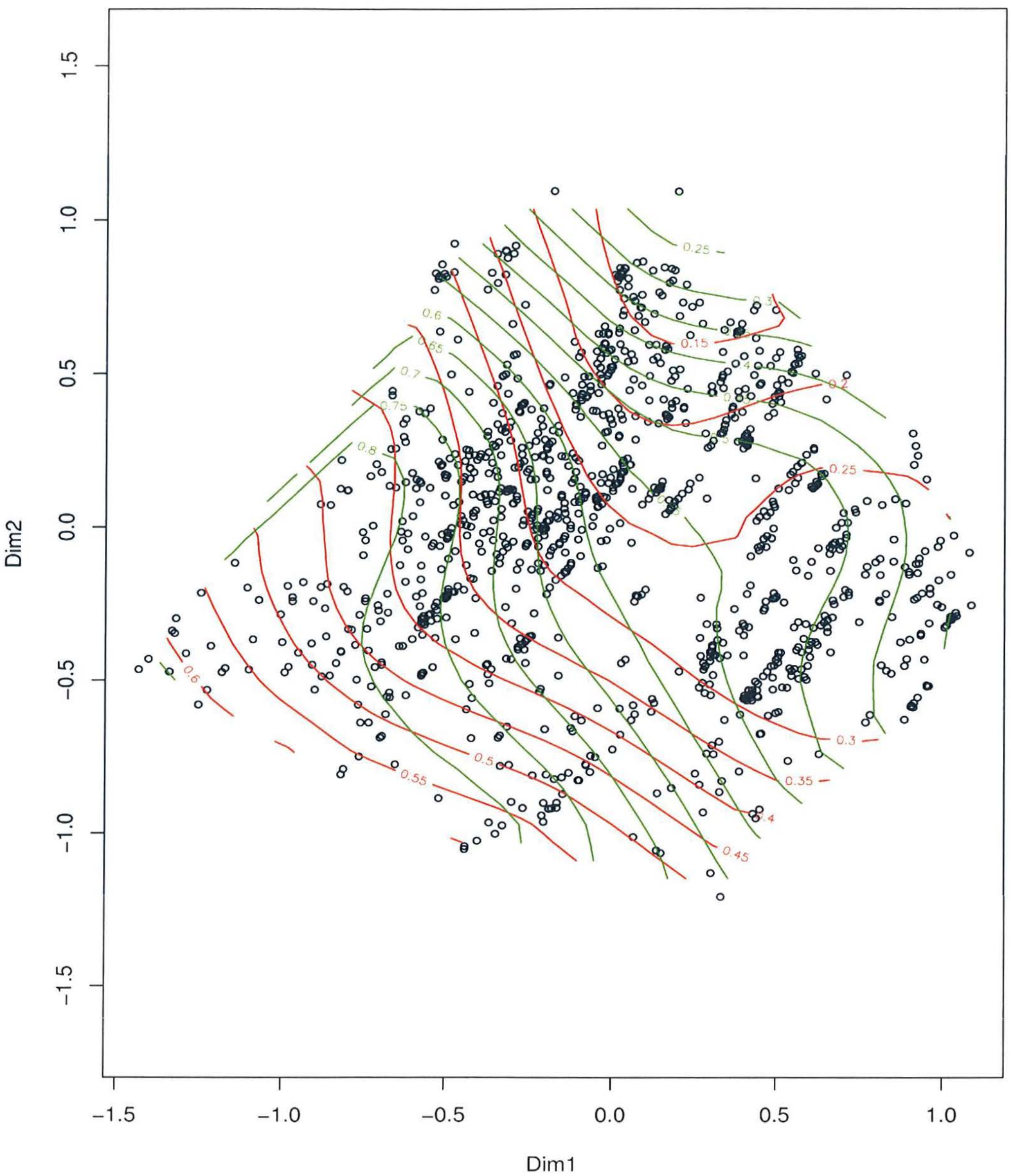

Figure 5

Thinplate spline smoothing contours overlay on ordination plot. Red lines show bulk density in kg per cubic metre for the upper horizon and green lines show bulk density in kg per cubic metre for the lower horizons.

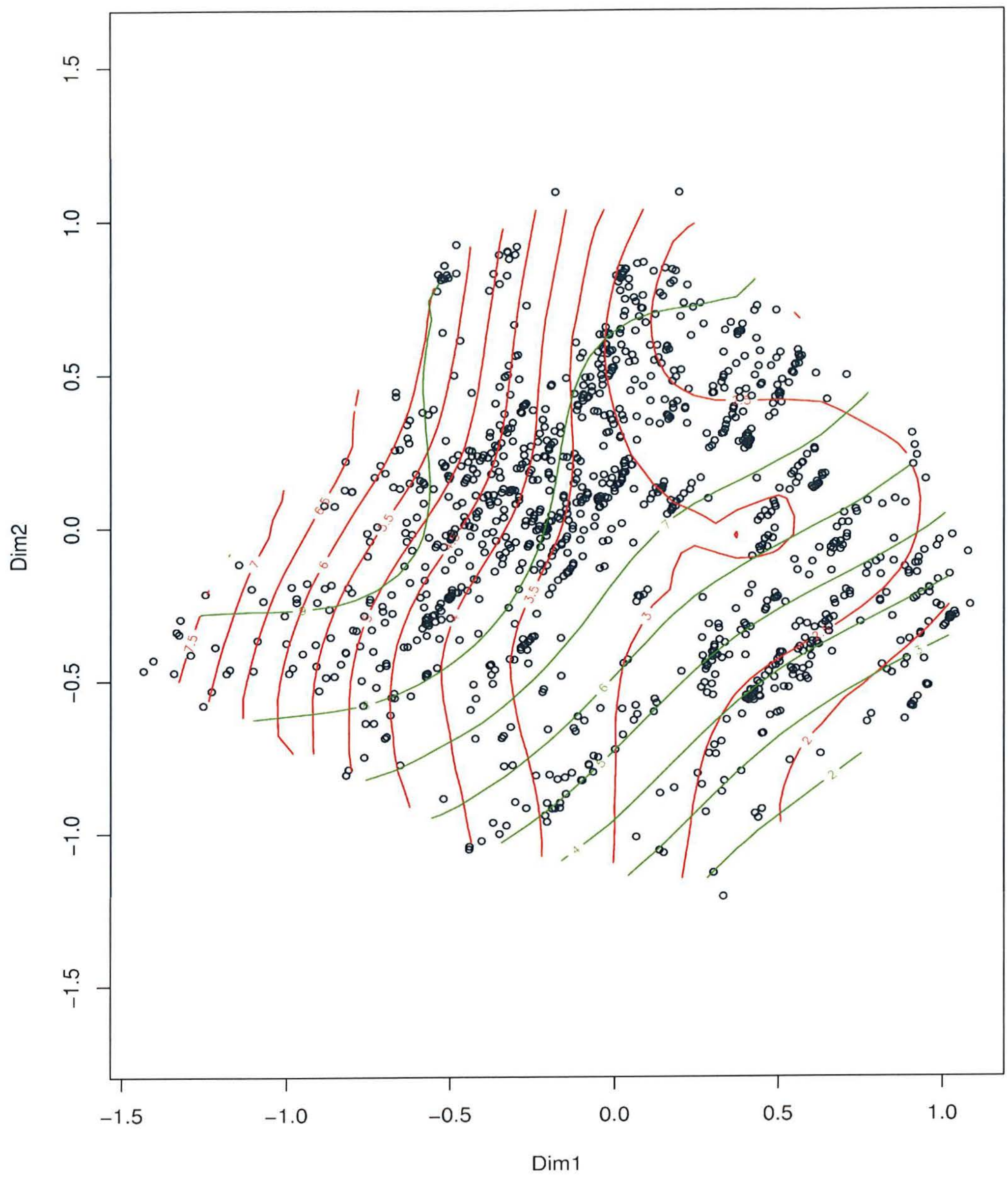

Figure 6

Thinplate spline smoothing contours overlay on ordination plot. Red lines show humification classes for the upper horizon and green lines show humification classes for the lower horizons.

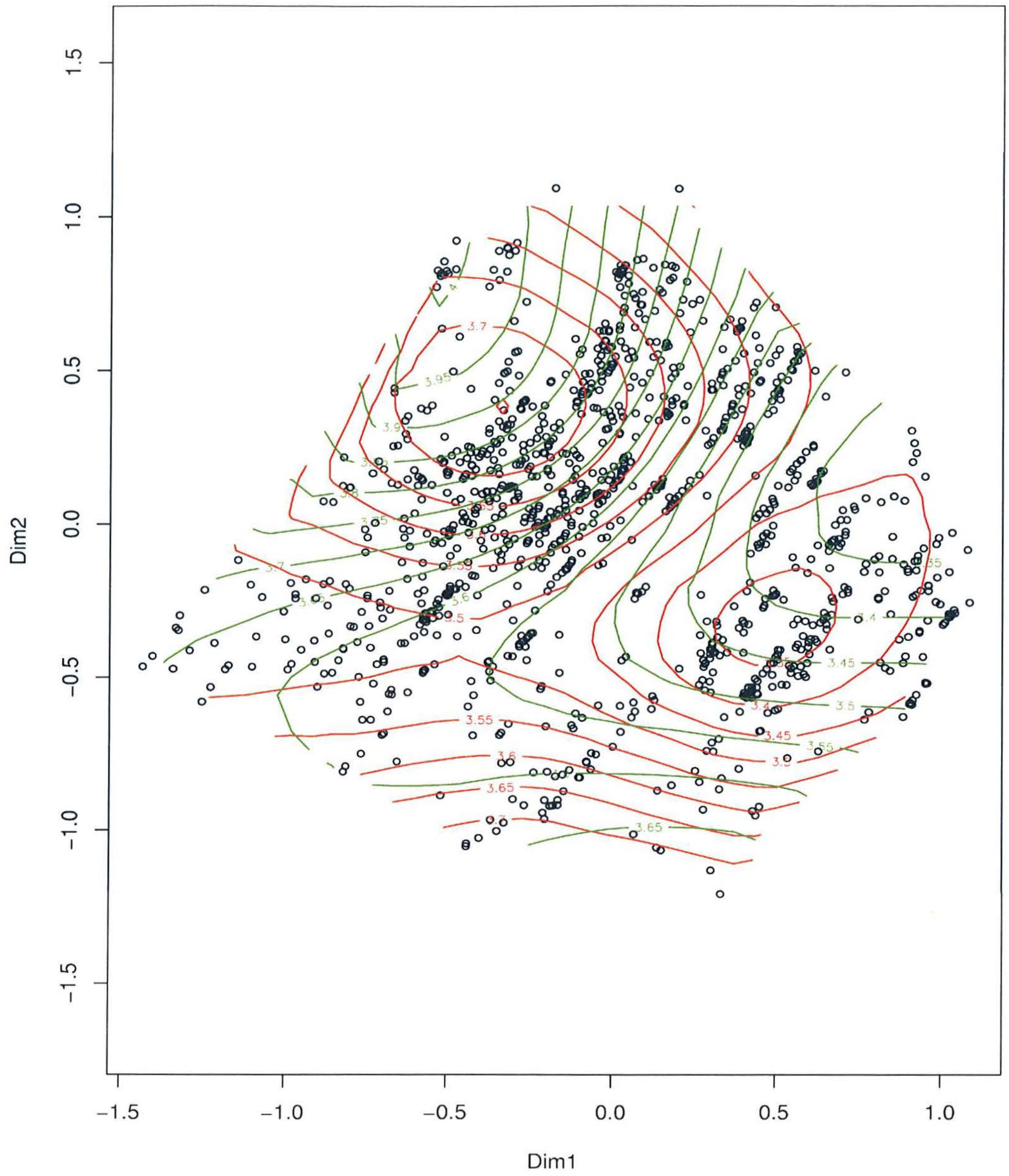

Figure 7

Thinplate spline smoothing contours overlay on ordination plot. Red lines show pH for the upper horizon and green lines show pH for the lower horizons.

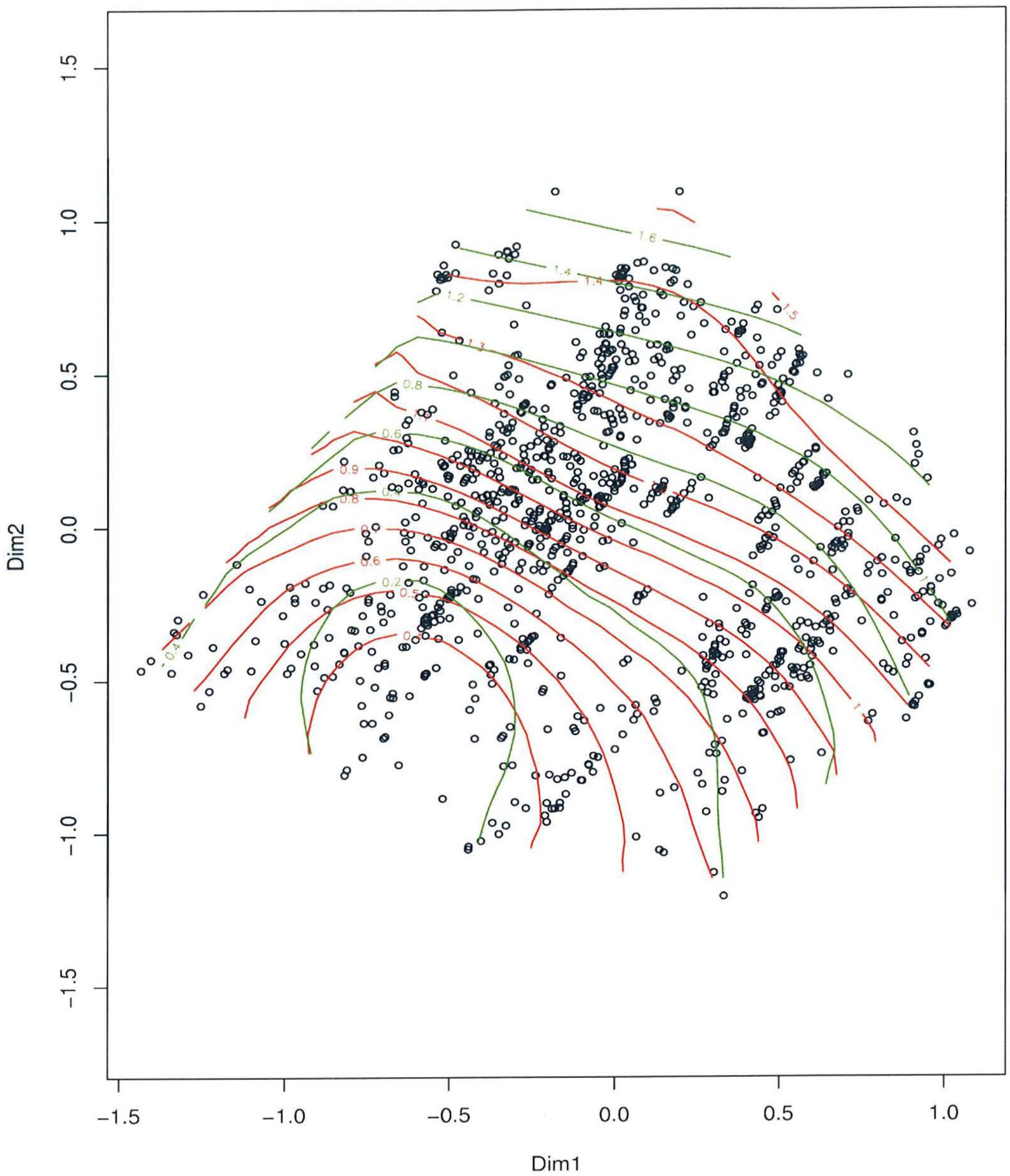

Figure 8

Thinplate spline smoothing contours overlay on ordination plot. Red lines show nitrogen content as a percentage of the soil dry weight for the upper horizon and green lines show nitrogen content as a percentage of the soil dry weight or the lower horizons.

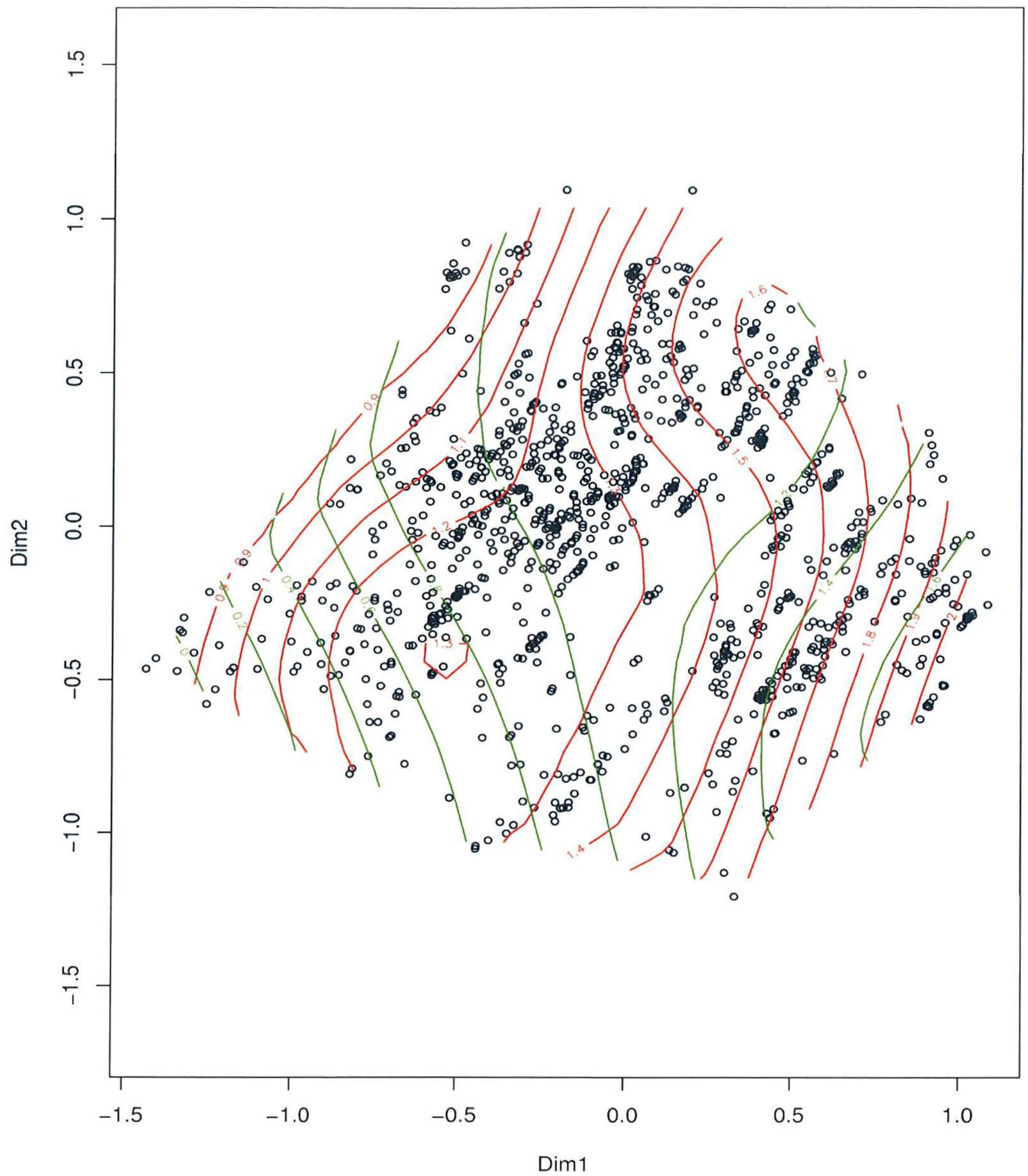

Figure 9

Thinplate spline smoothing contours overlay on ordination plot. Red lines show chroma classes for the upper horizon and green lines show chroma classes for the lower horizons.

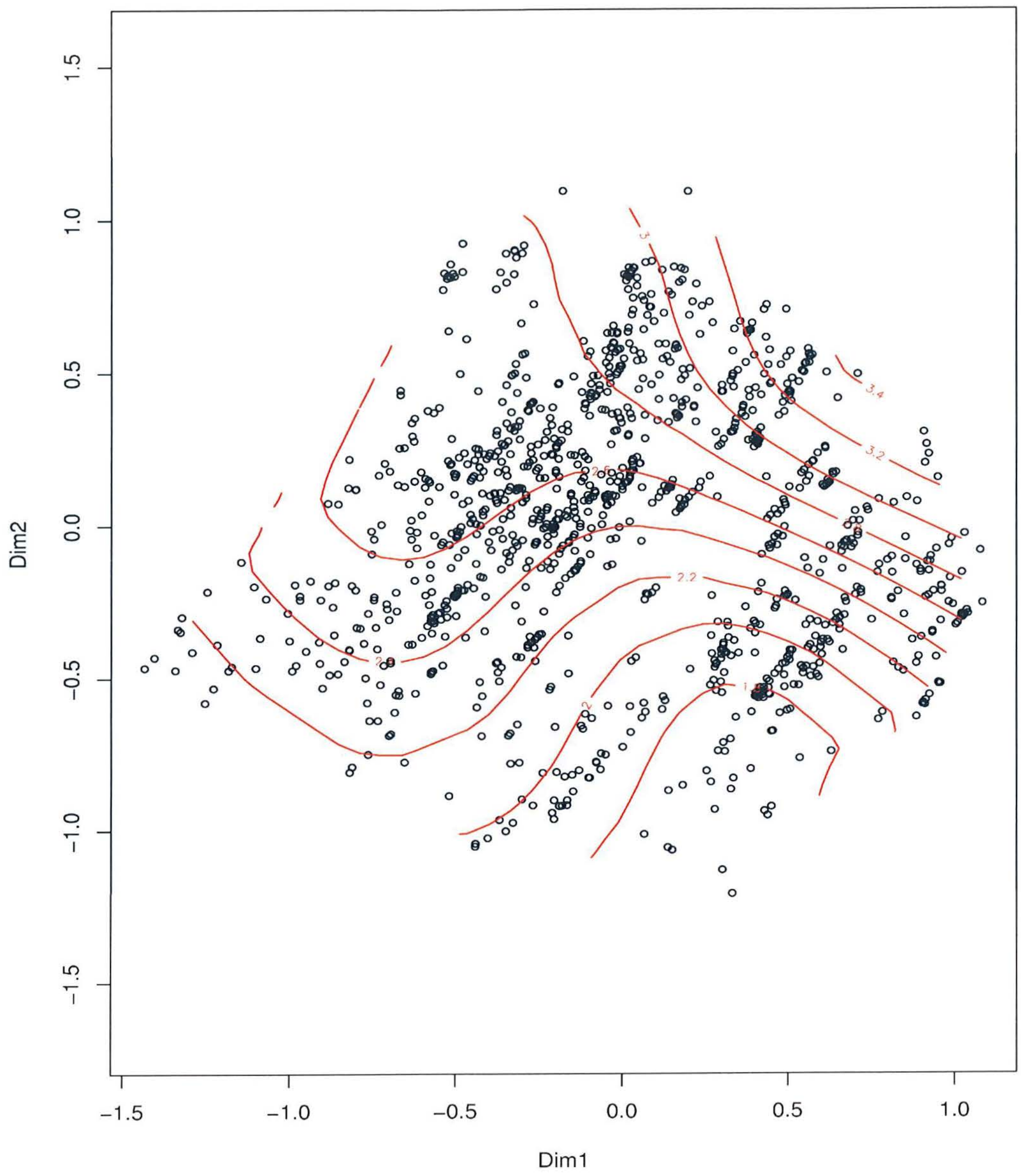

Figure 10

Thinplate spline smoothing contours overlay on ordination plot. Red lines show the number of horizons in the soil profile.

Appendix 5

The following boxplots show the soil characteristics for each cluster group found through the analysis performed in Chapter 3. The median is represented by the solid black line within the blue box, each end of the box is the first and third quartiles, the whiskers extend to the range times the interquartile range of the data extremes and the points are extreme outliers. The measures of each variable is explained in the Methods Section of Chapter 3.

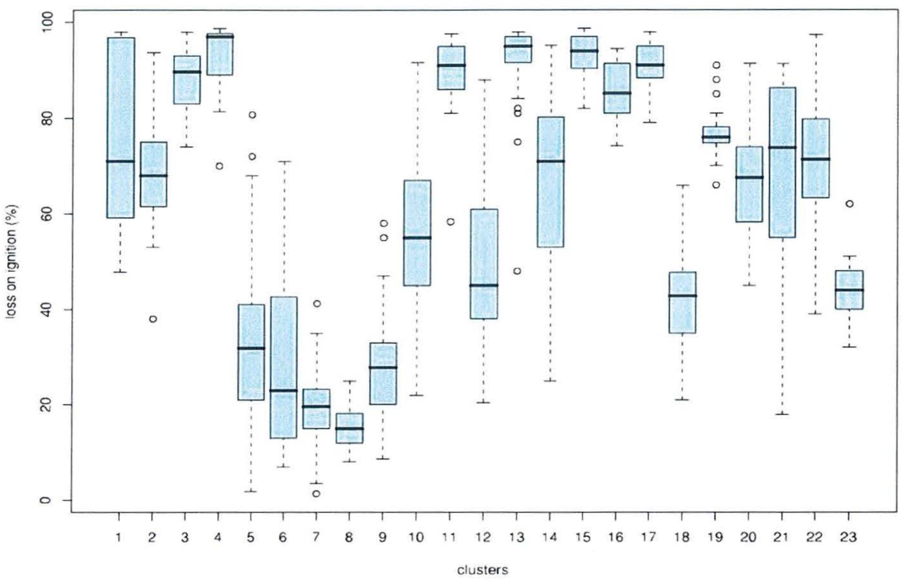

Figure 1

Boxplot showing percent organic material in the upper horizon as measured through loss on ignition, for each cluster group. A division by 2 will yield the percent organic carbon.

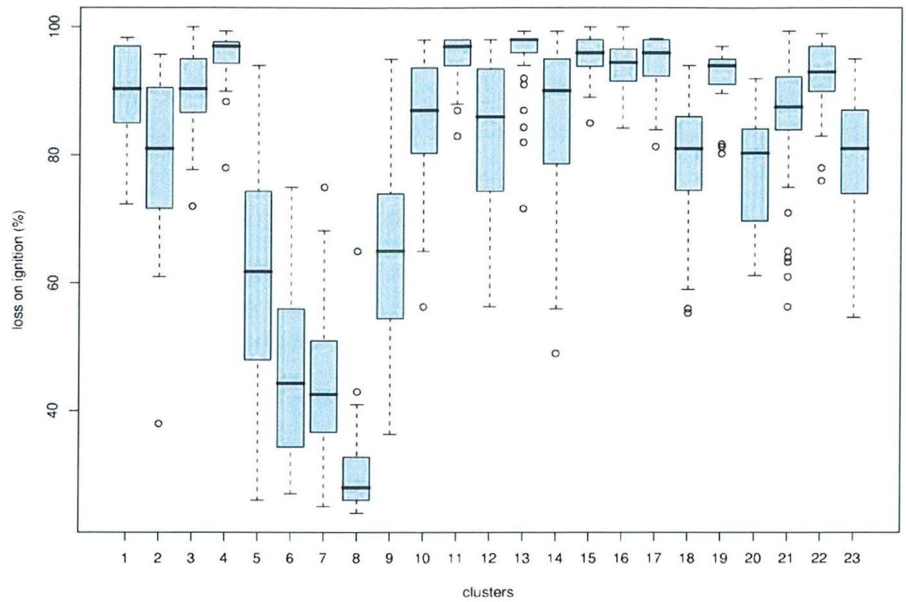

Figure 2

Boxplot showing percent organic material in the lower horizons as measured through loss on ignition, for each cluster group. A division by 2 will yield the percent organic carbon.

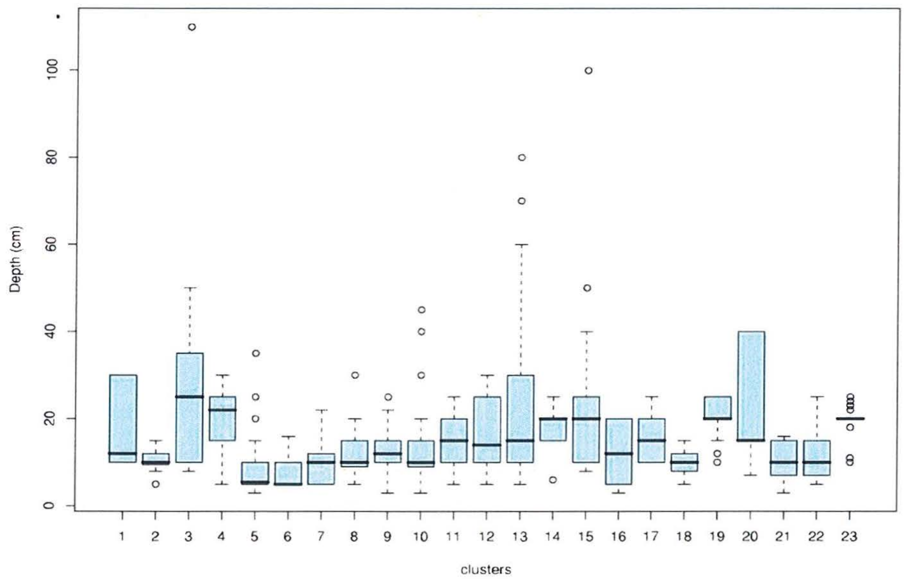

Figure 3

Boxplot showing the summary of depth of the upper horizon for each cluster group.

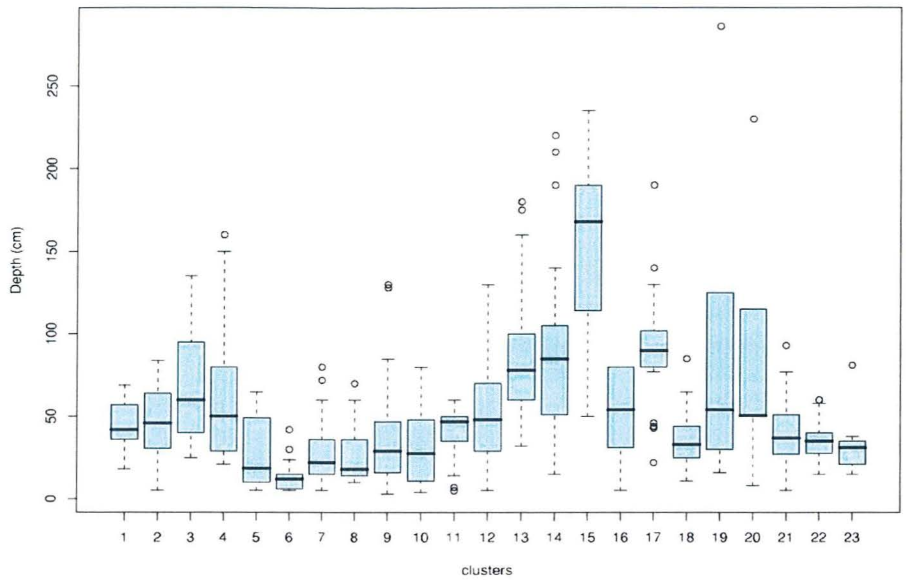

Figure 4

Boxplot showing the summary of depth of the lower horizons for each cluster group.

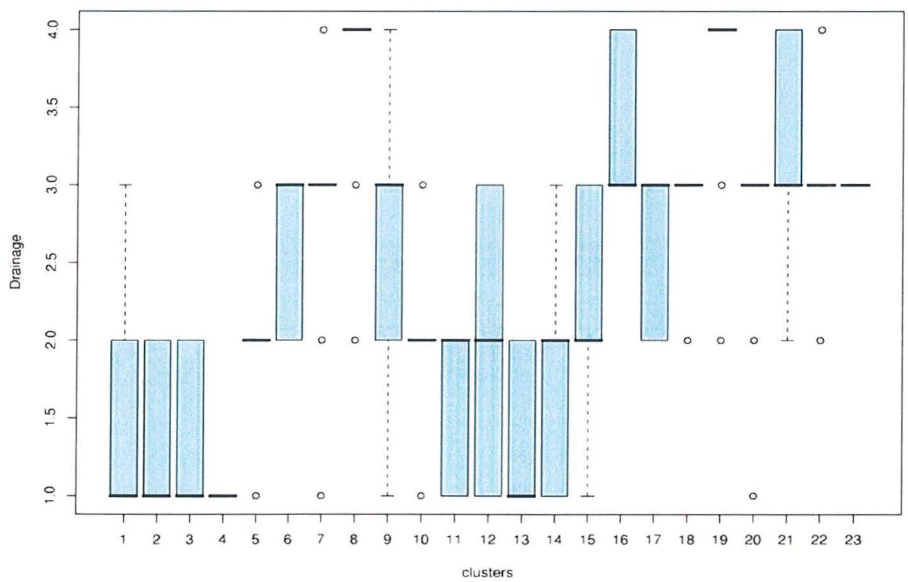

Figure 5

Boxplot showing summary of drainage class association in the upper horizon for each cluster group.

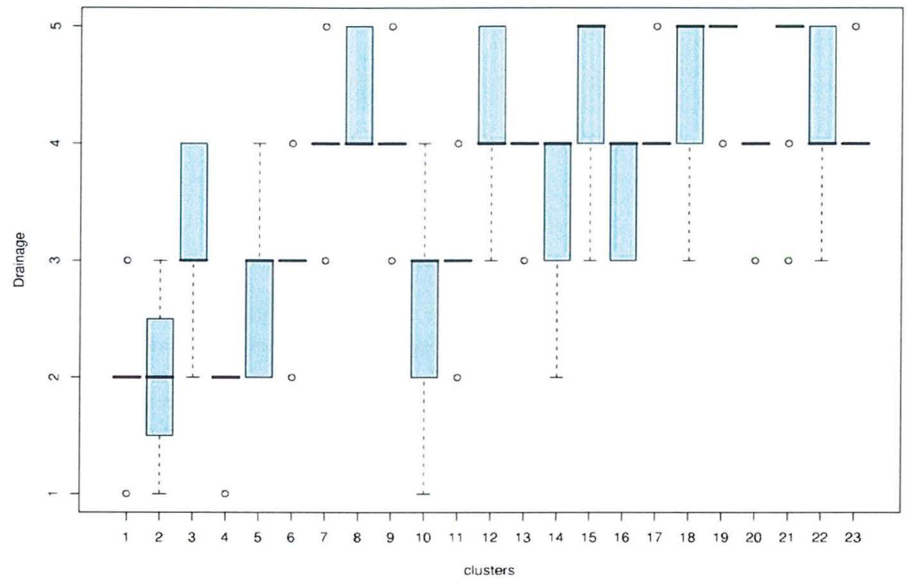

Figure 6

Boxplot showing summary of drainage class association in the lower horizons for each cluster group.

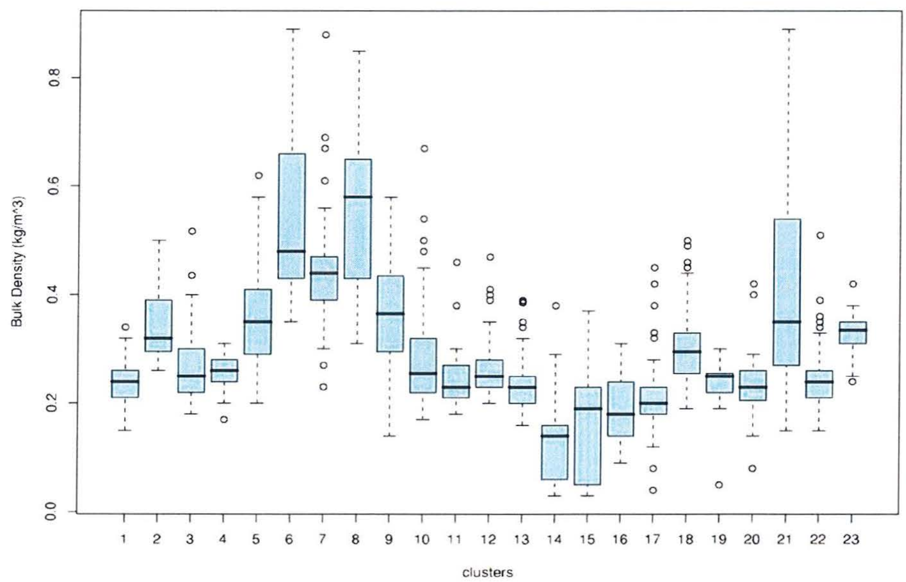

Figure 7

Boxplot showing the summary of bulk density of the upper horizon for each cluster group.

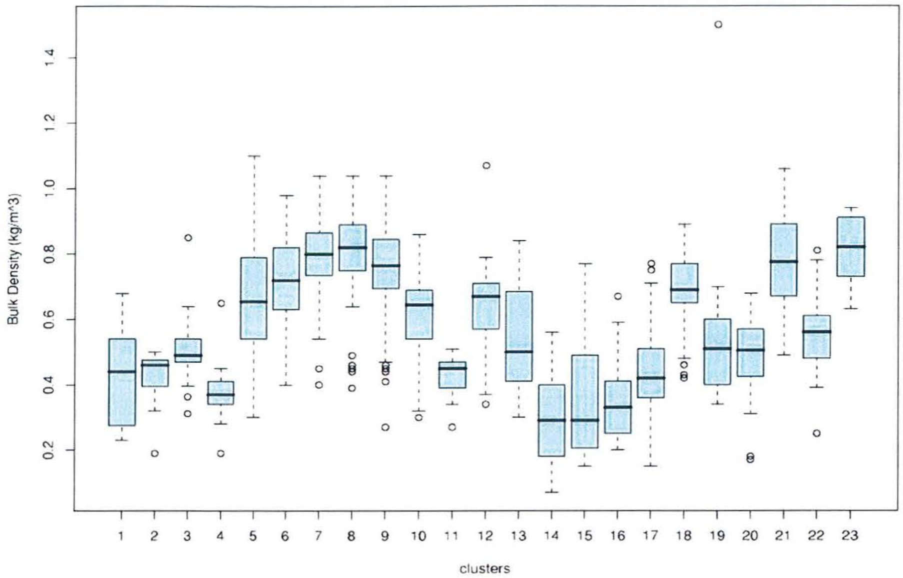

Figure 8

Boxplot showing the summary of bulk density of the lower horizons for each cluster group.

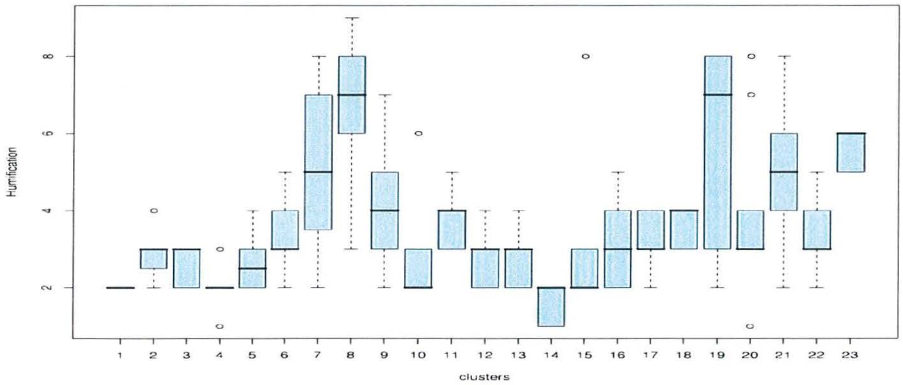

Figure 9

Boxplot showing the summary of humification class of the upper horizon for each cluster group.

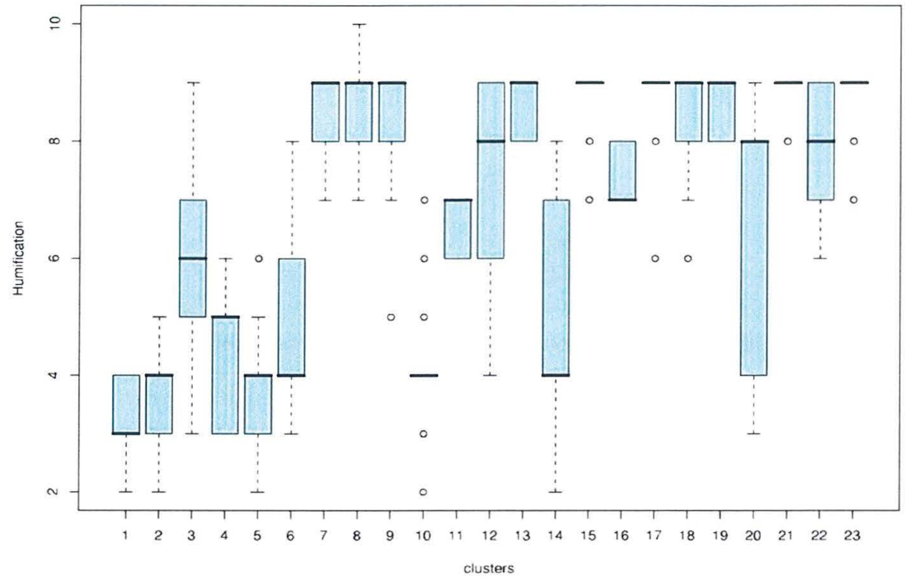

Figure 10

Boxplot showing the summary of humification class of the lower horizons for each cluster group.

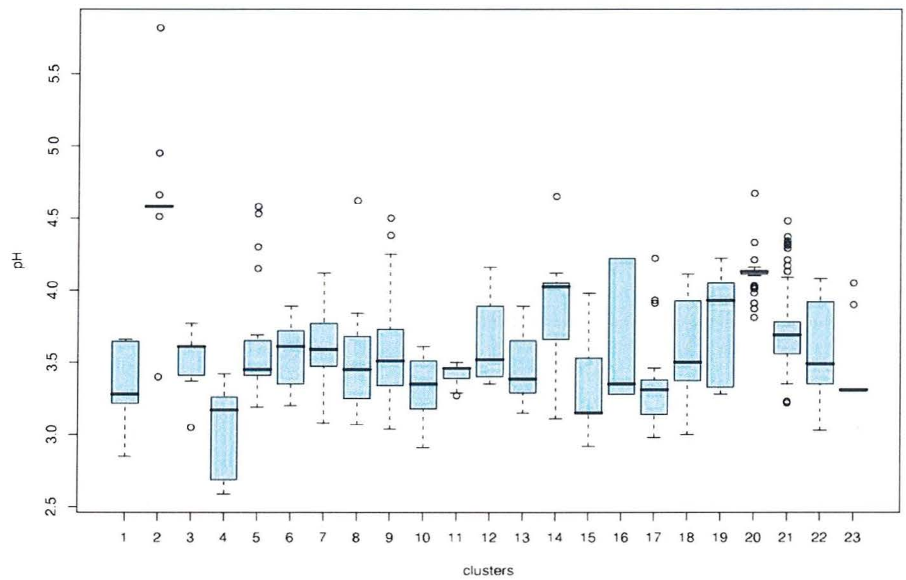

Figure 11

Boxplot showing the summary of pH of the upper horizon for each cluster group.

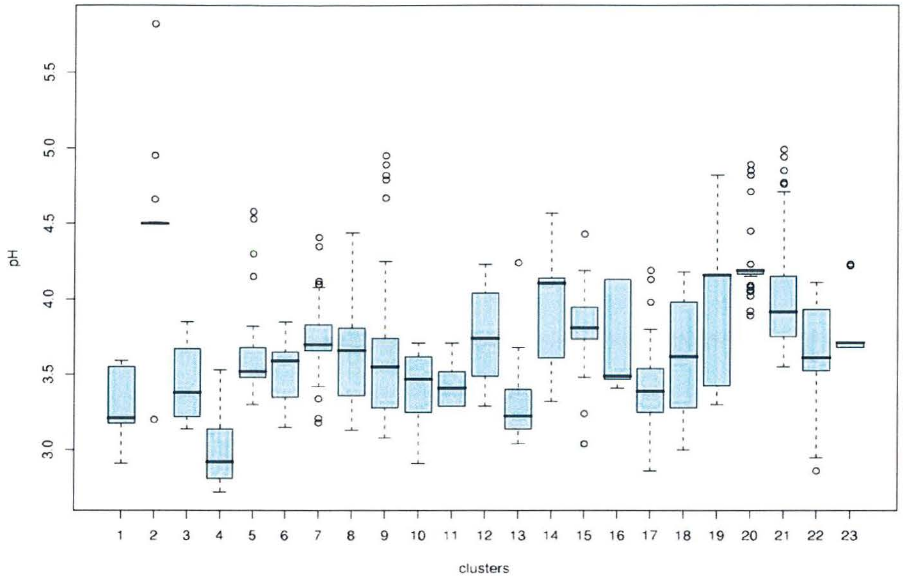

Figure 12

Boxplot showing the summary of pH of the lower horizons for each cluster group.

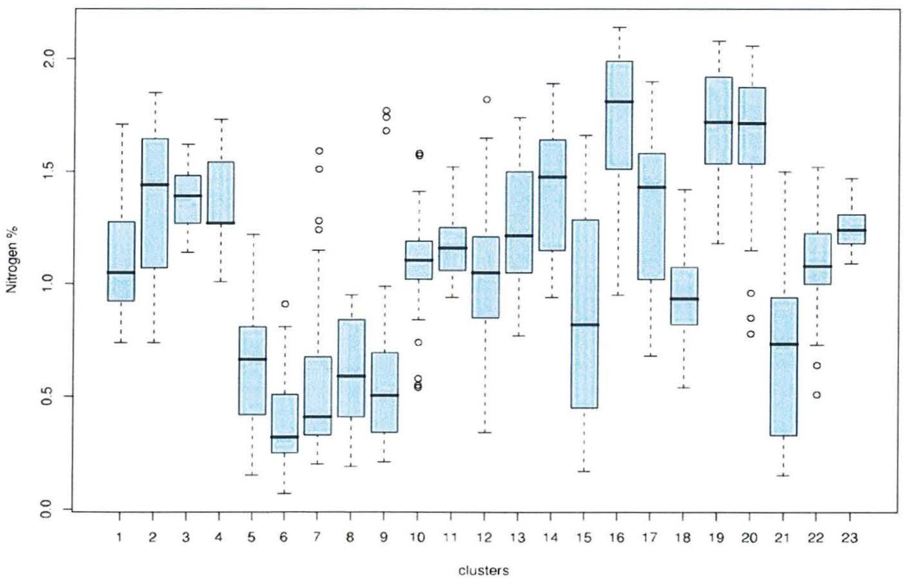

Figure 13

Boxplot showing the summary of nitrogen content of the upper horizon for each cluster group.

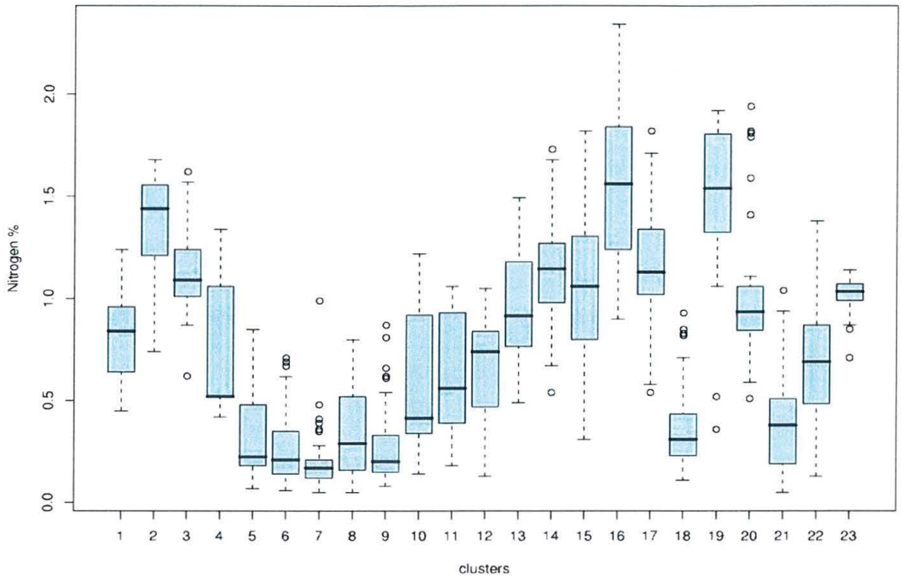

Figure 14

Boxplot showing the summary of nitrogen content of the lower horizons for each cluster group.

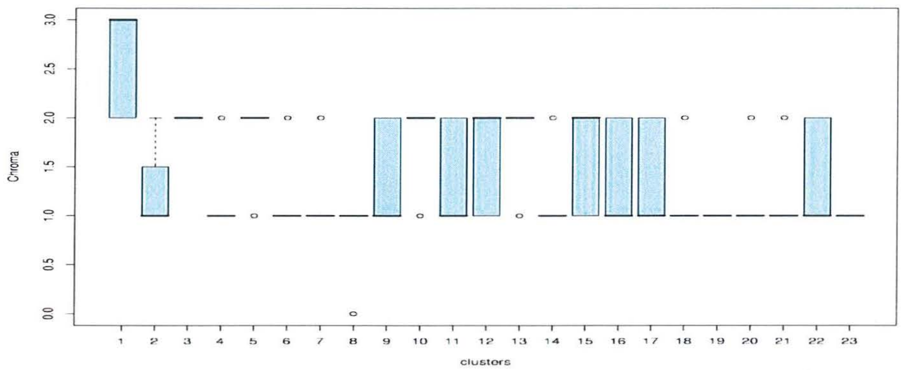

Figure 15

Boxplot showing the summary of chroma classes of the upper horizon for each cluster group.

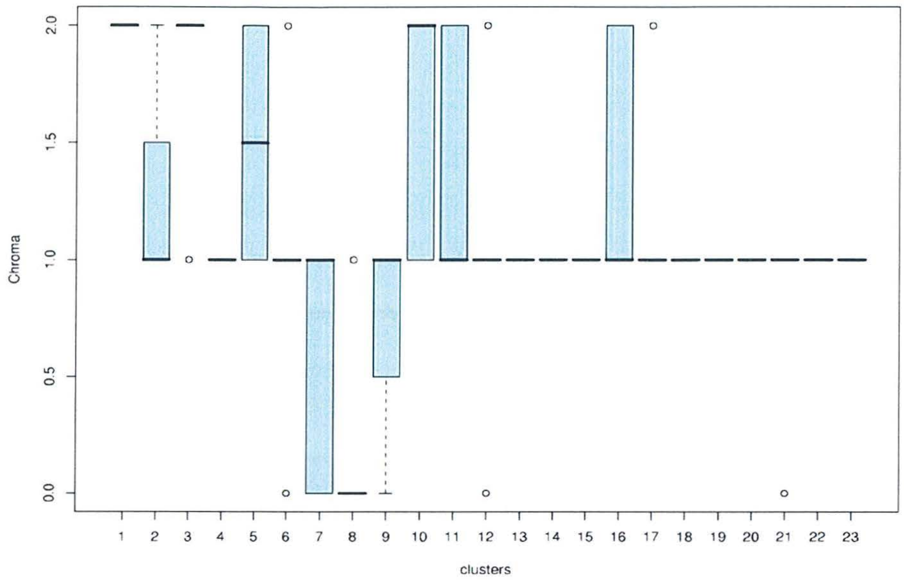

Figure 16

Boxplot showing the summary of chroma classes of the lower horizons for each cluster group.

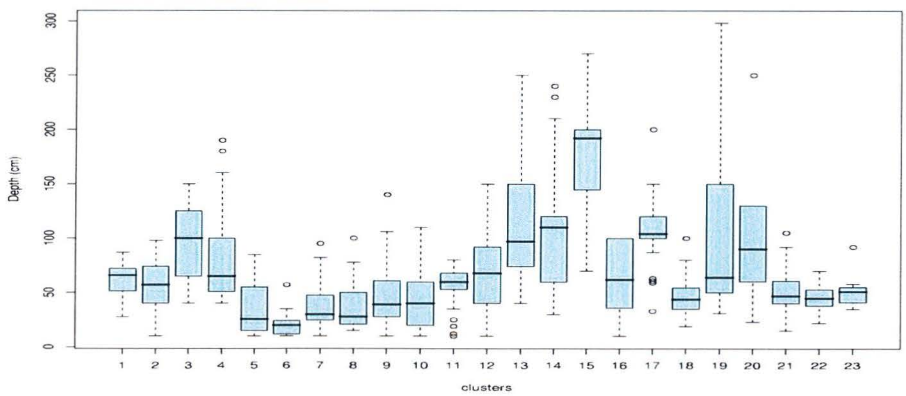

Figure 17

Boxplot showing the summary of the total depth of soil for each cluster group.

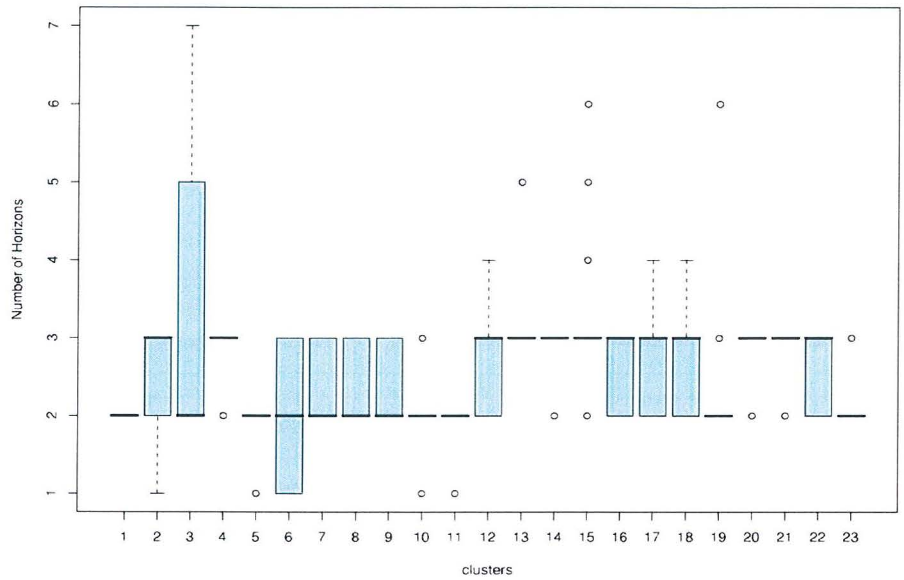

Figure 18

Boxplot showing the summary of the number of horizons in the soil profile for each cluster group.

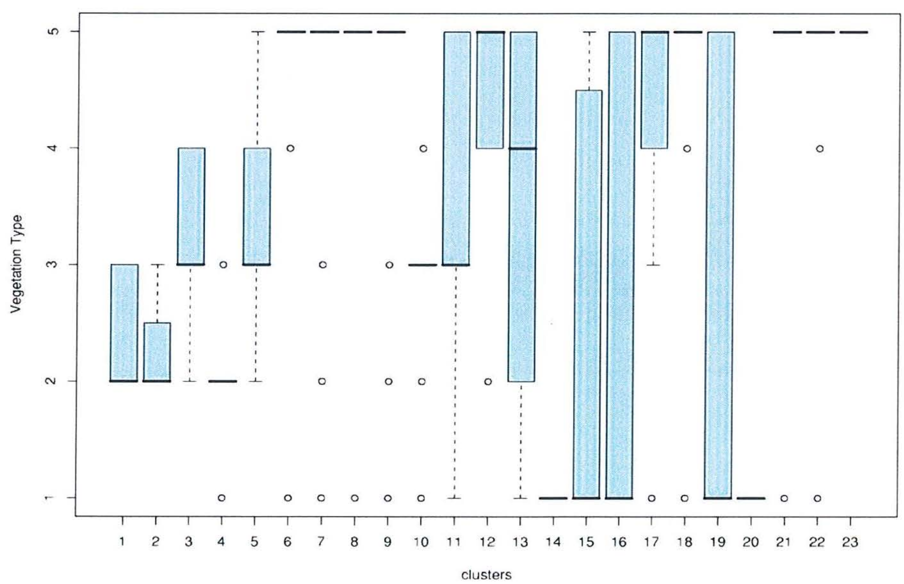

Figure 19

Boxplot showing the summary of the vegetation type classes for each cluster group.

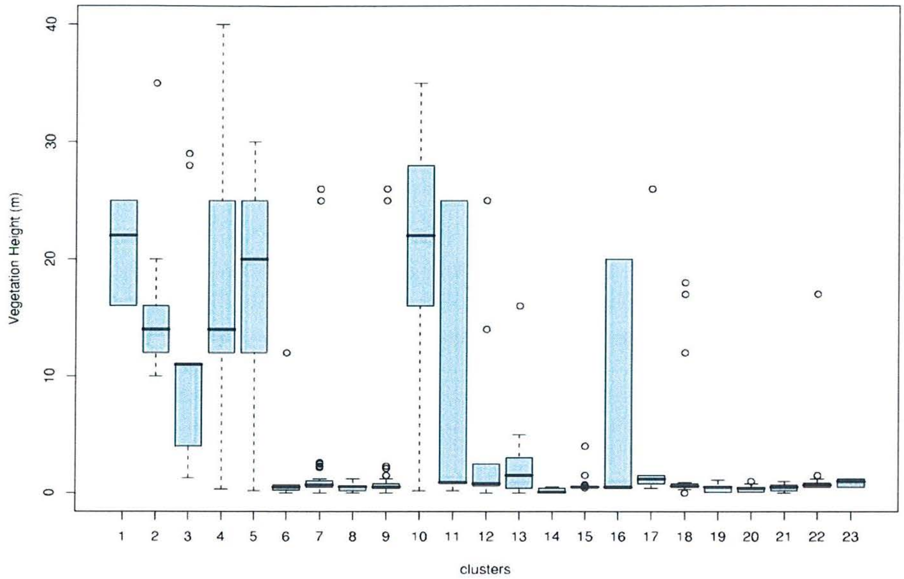

Figure 20

Boxplot showing the summary of the vegetation height for each cluster group.

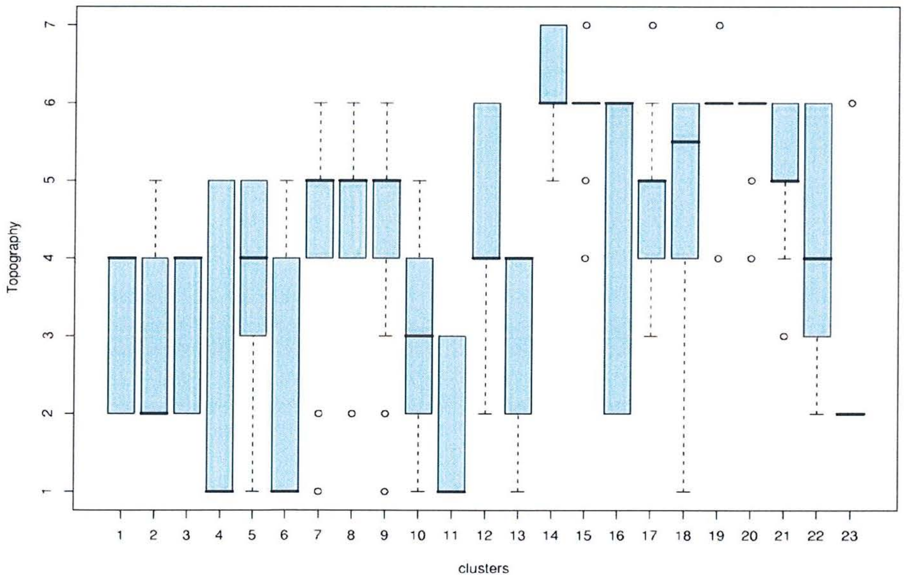

Figure 21

Boxplot showing the summary of the topography classes for each cluster group.

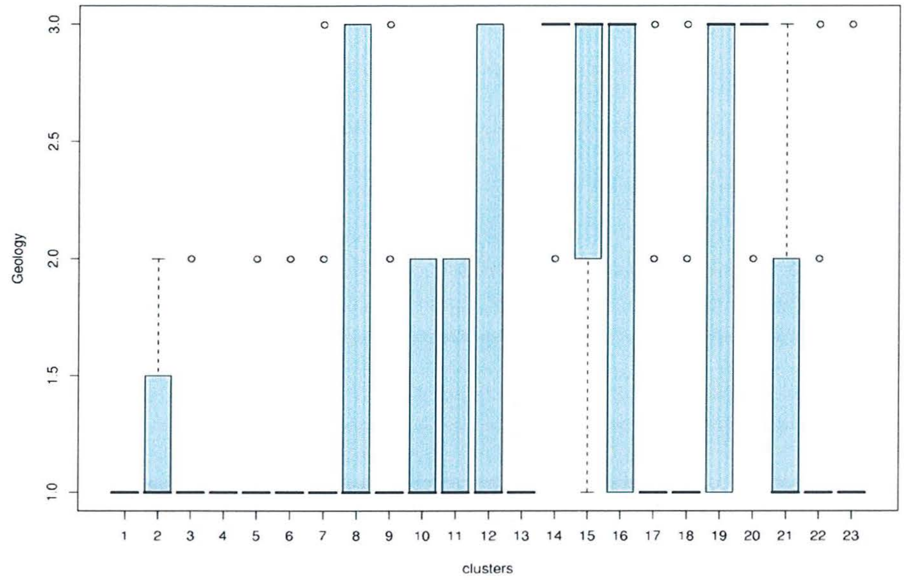

Figure 22

Boxplot showing the summary of the geology classes for each cluster group.

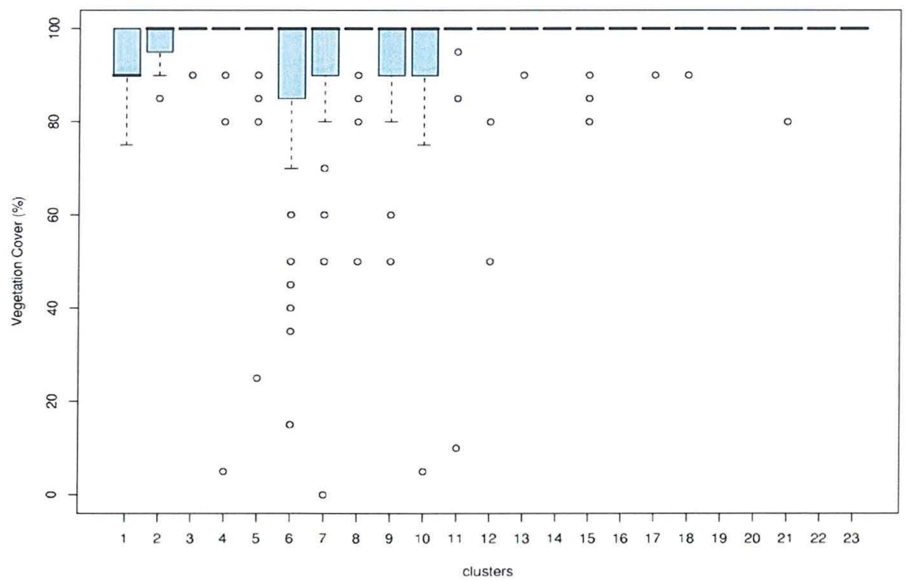

Figure 23

Boxplot showing the summary of the vegetation cover for each cluster group.

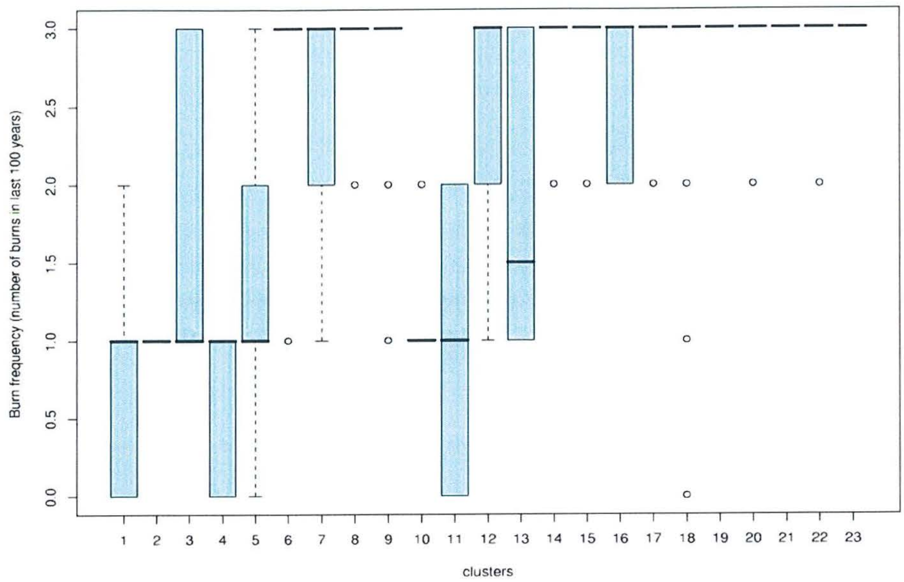

Figure 24

Boxplot showing the summary of the burn frequency classes for each cluster group.

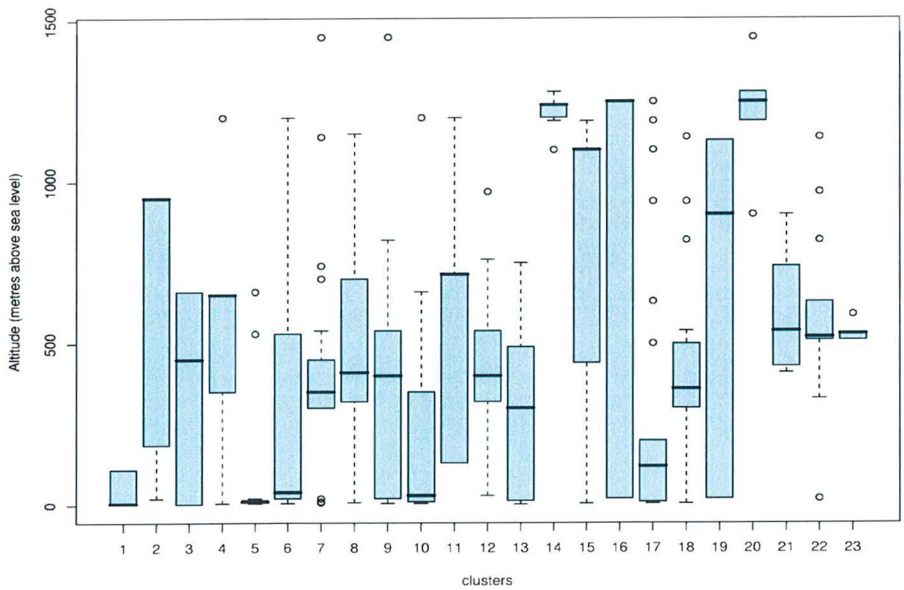

Figure 25

Boxplot showing the summary of the altitude for each cluster group.

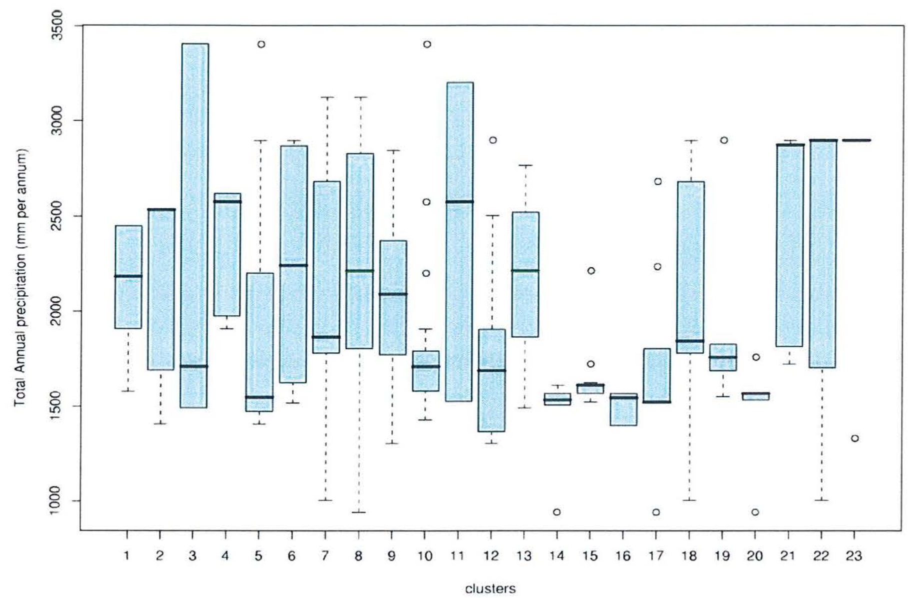

Figure 26

Boxplot showing the summary of the total annual precipitation for each cluster group.

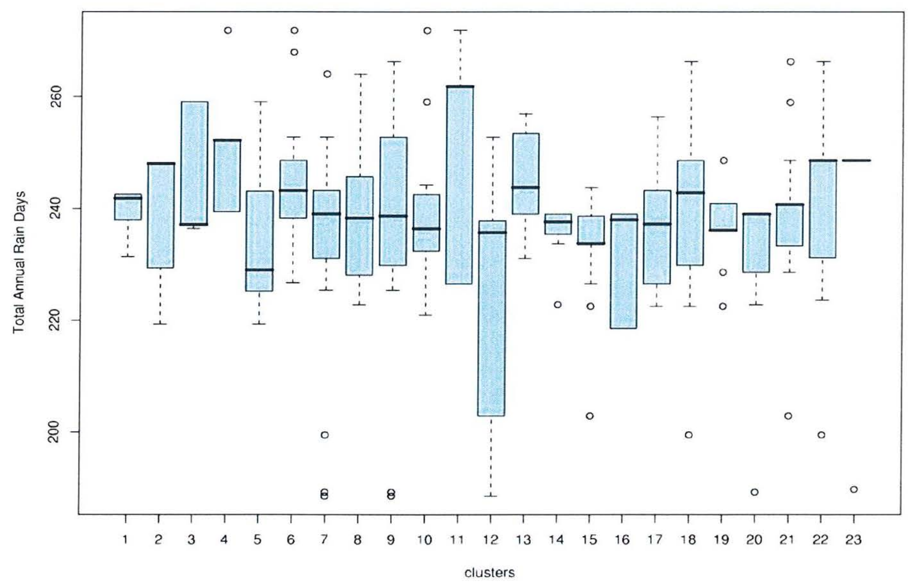

Figure 27

Boxplot showing the summary of total annual rain days for each cluster group.

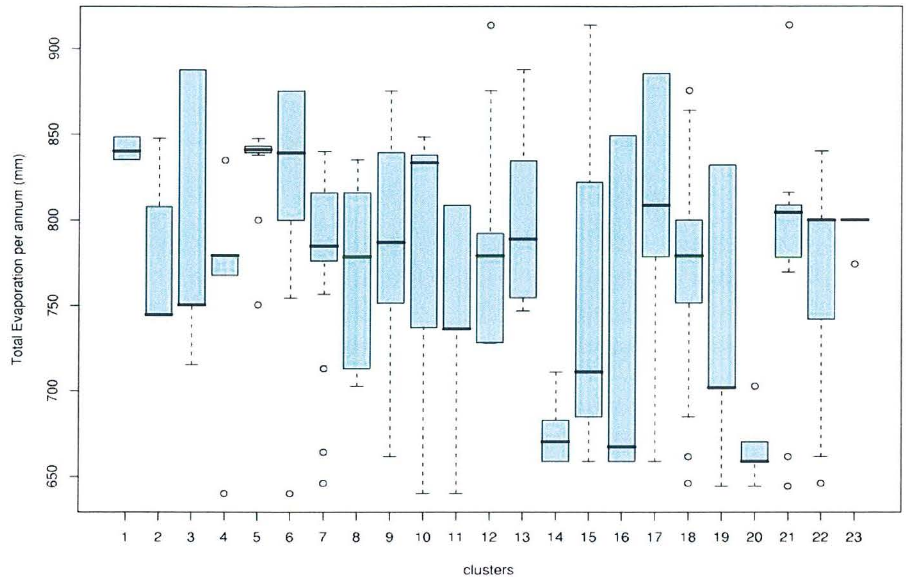

Figure 28

Boxplot showing the summary of the total annual evaporation for each cluster group.

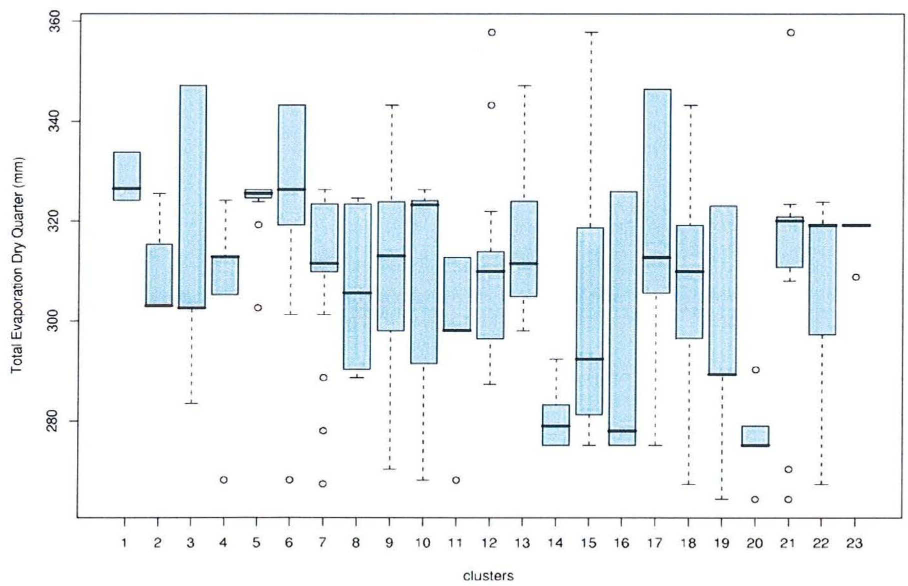

Figure 29

Boxplot showing the summary of the total evaporation for the driest quarter of the year for each cluster group.

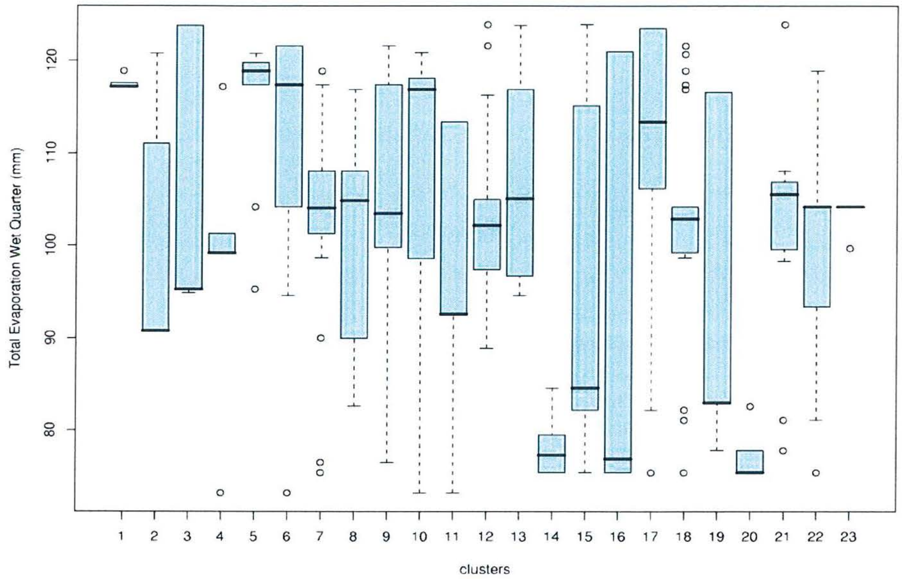

Figure 30

Boxplot showing the summary of the total evaporation for the wettest quarter of the year for each cluster group.

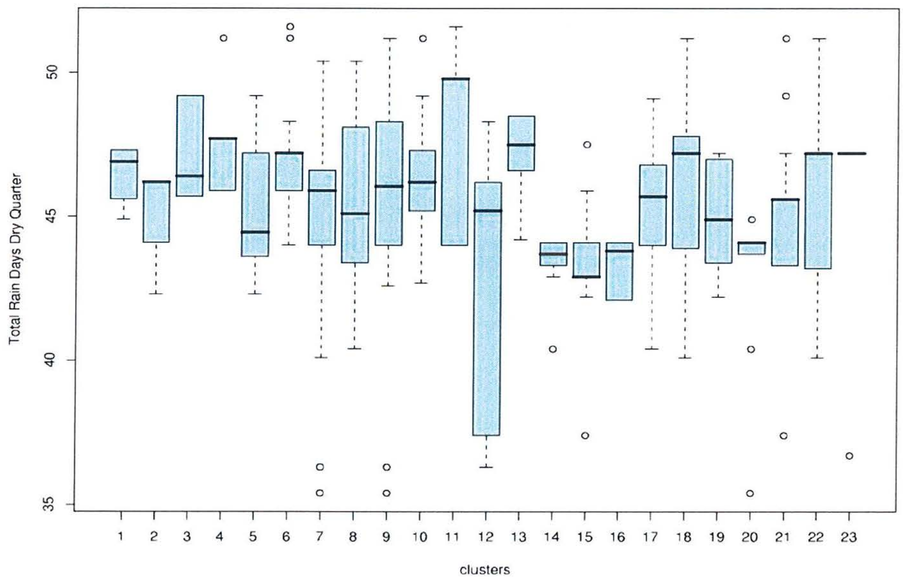

Figure 31

Boxplot showing the summary of the total number of rain days for the driest quarter of the year for each cluster group.

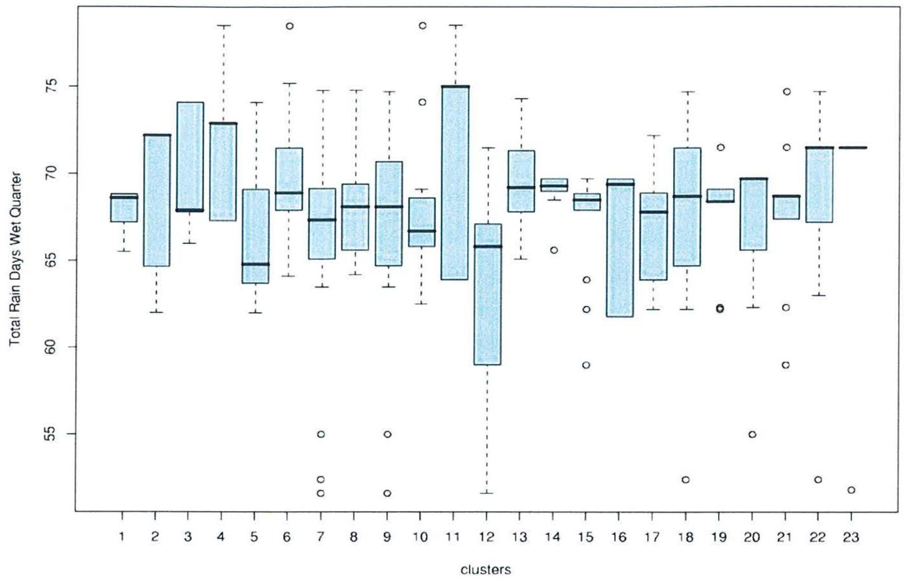

Figure 32

Boxplot showing the summary of the total number of rain days for the wettest quarter of the year for each cluster group.

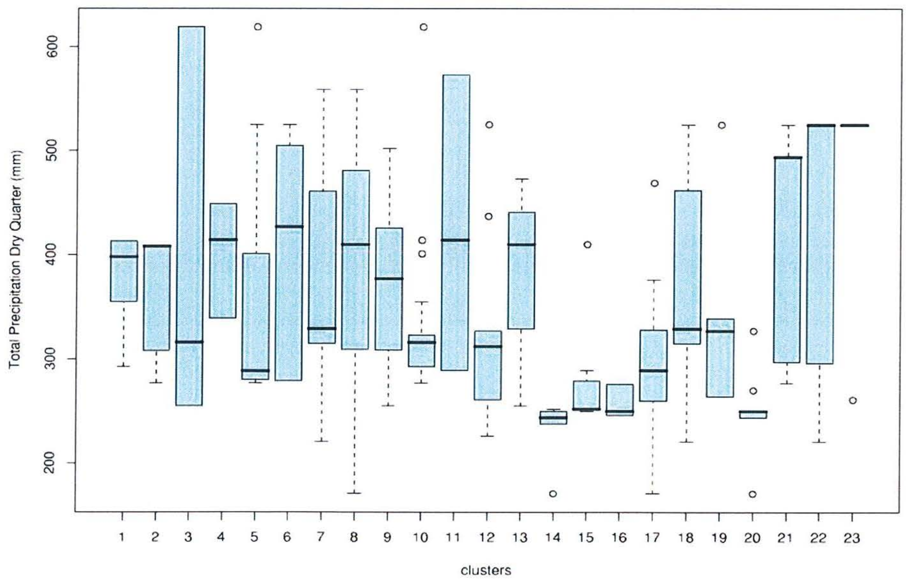

Figure 33

Boxplot showing the summary of the total precipitation for the driest quarter of the year for each cluster group.

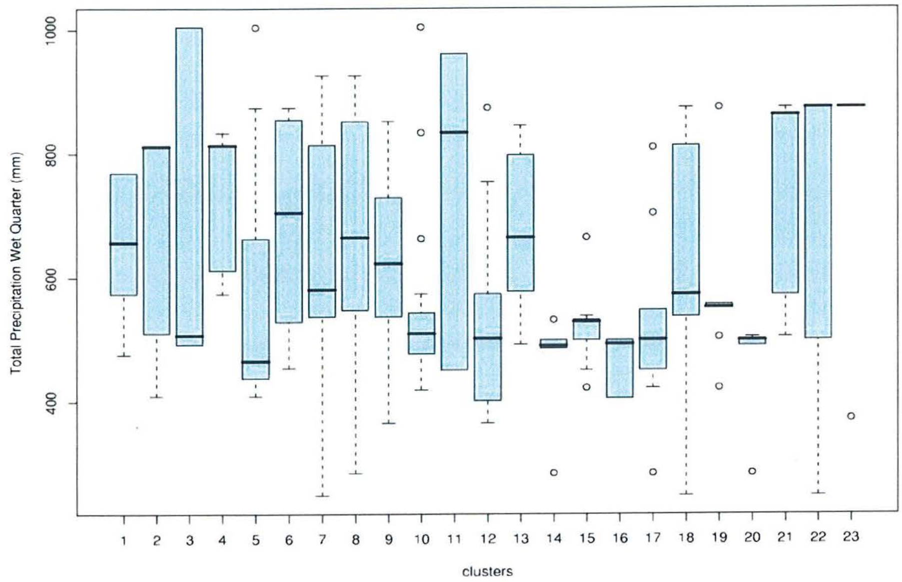

Figure 34

Boxplot showing the summary of the total precipitation for the wettest quarter of the year for each cluster group.

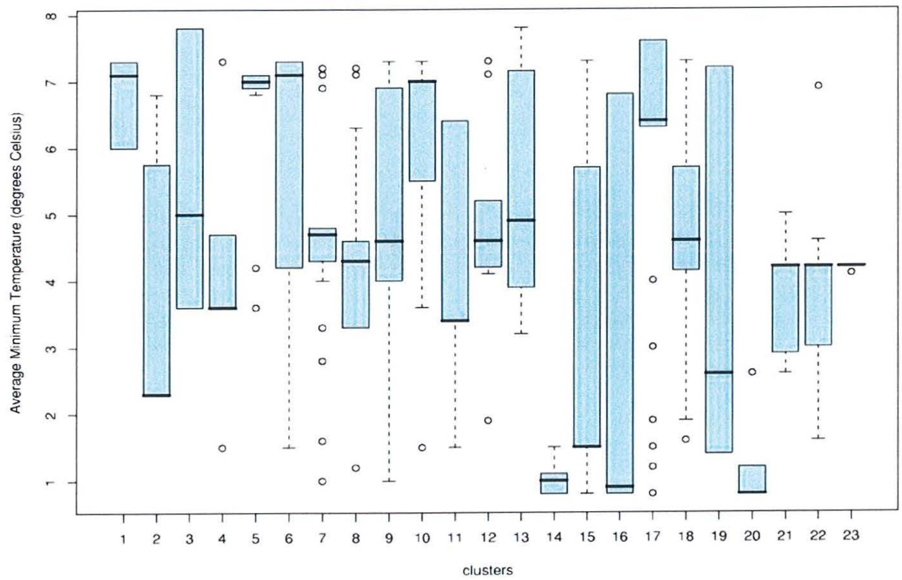

Figure 35

Boxplot showing the summary of the average maximum temperature for each cluster group.

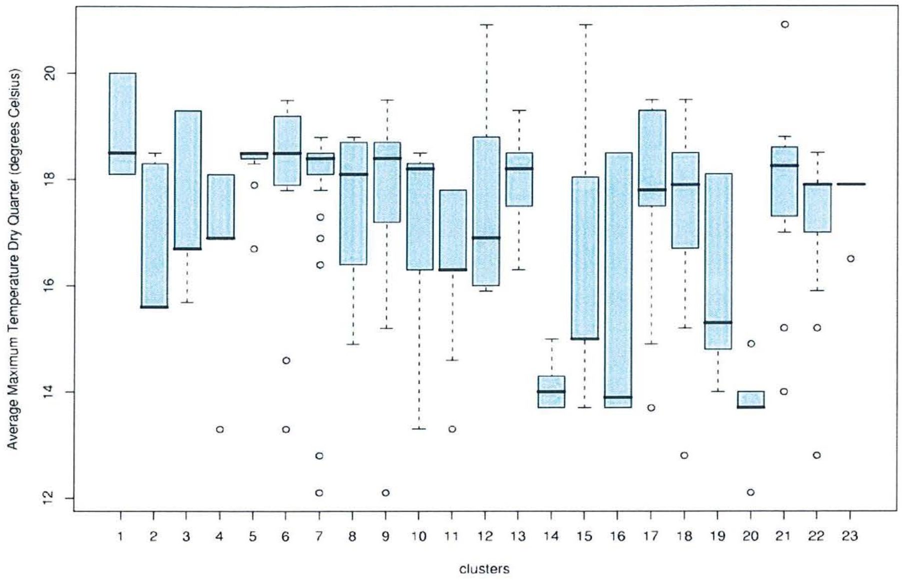

Figure 36

Boxplot showing the summary of the average maximum temperature for the driest quarter of the year for each cluster group.

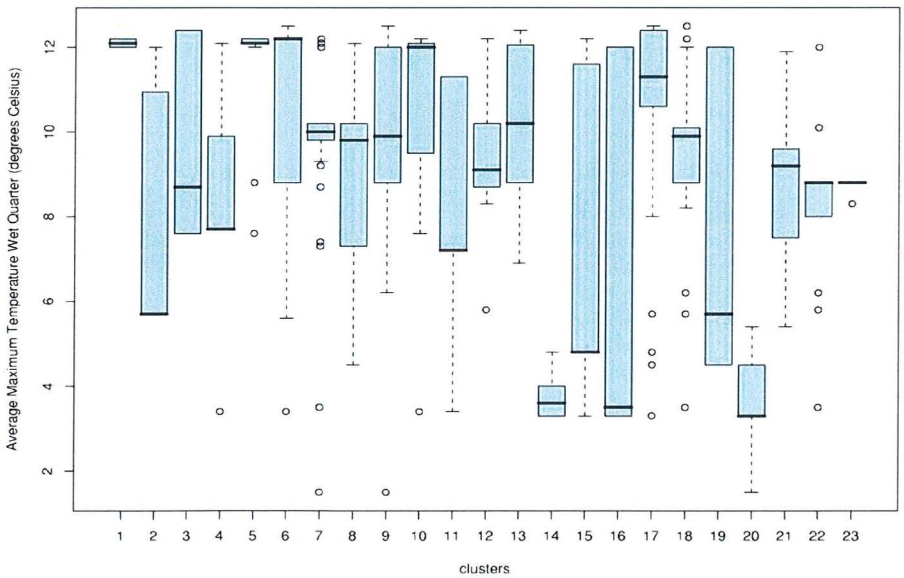

Figure 37

Boxplot showing the summary average maximum temperature for the wettest quarter of the year for each cluster group.

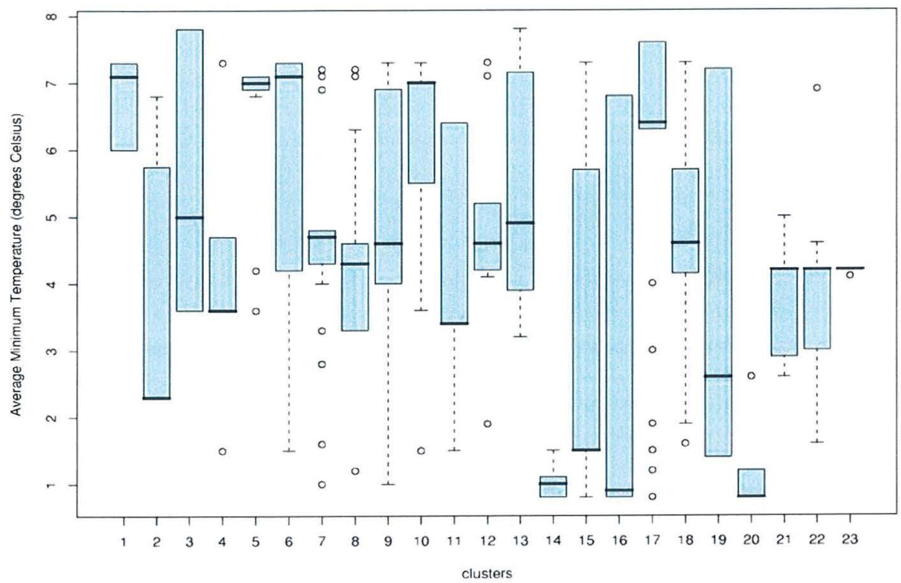

Figure 38

Boxplot showing the summary of the average minimum temperature for each cluster group.

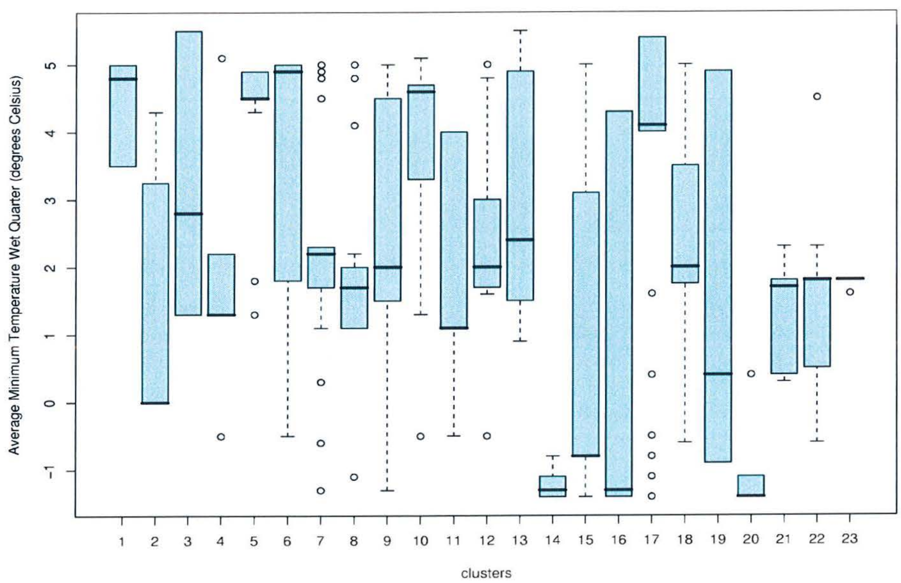

Figure 39

Boxplot showing the summary of the average minimum temperature for the wettest quarter of the year for each cluster group.

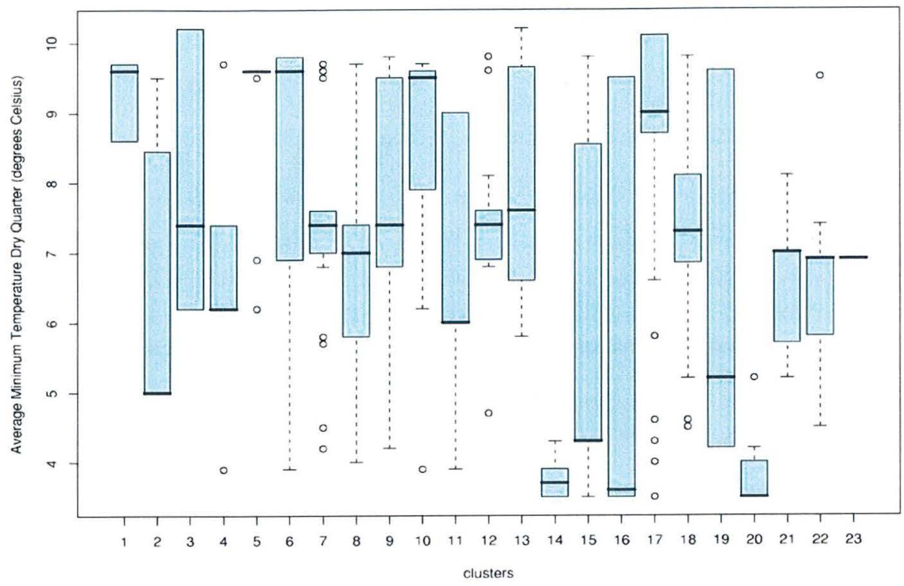

Figure 40

Boxplot showing the summary of the average minimum temperature for the driest quarter of the year for each cluster.

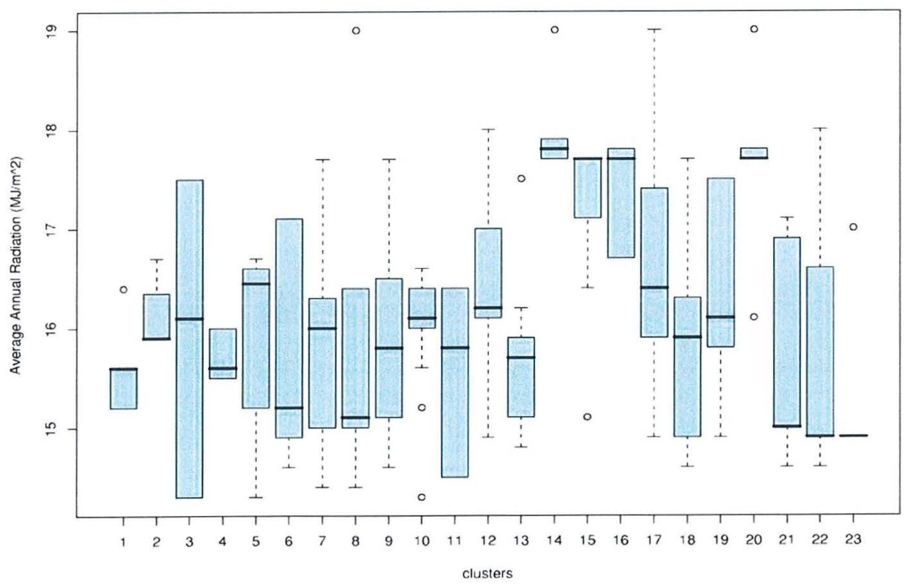

Figure 41

Boxplot showing the summary of the average annual radiation for each cluster group.

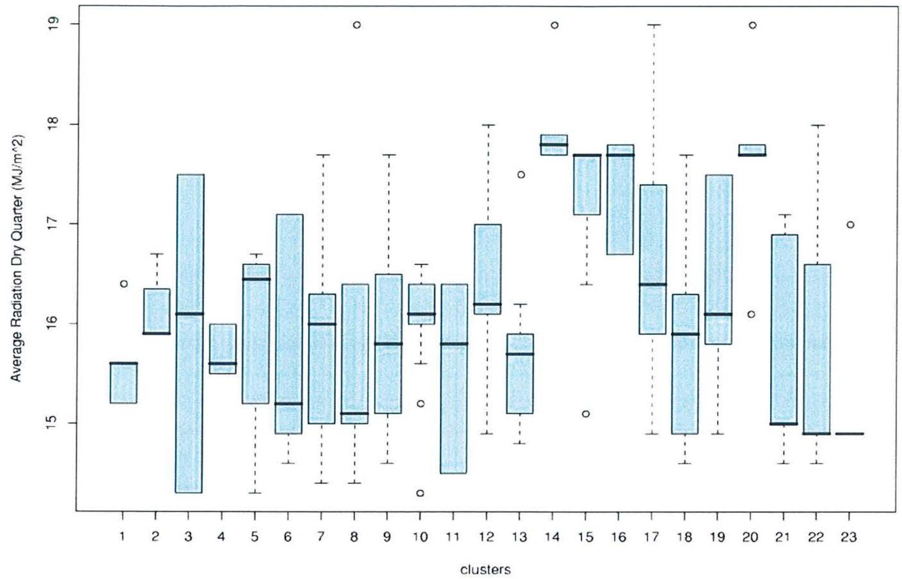

Figure 42

Boxplot showing the summary of the average radiation for the driest quarter of the year for each cluster group.

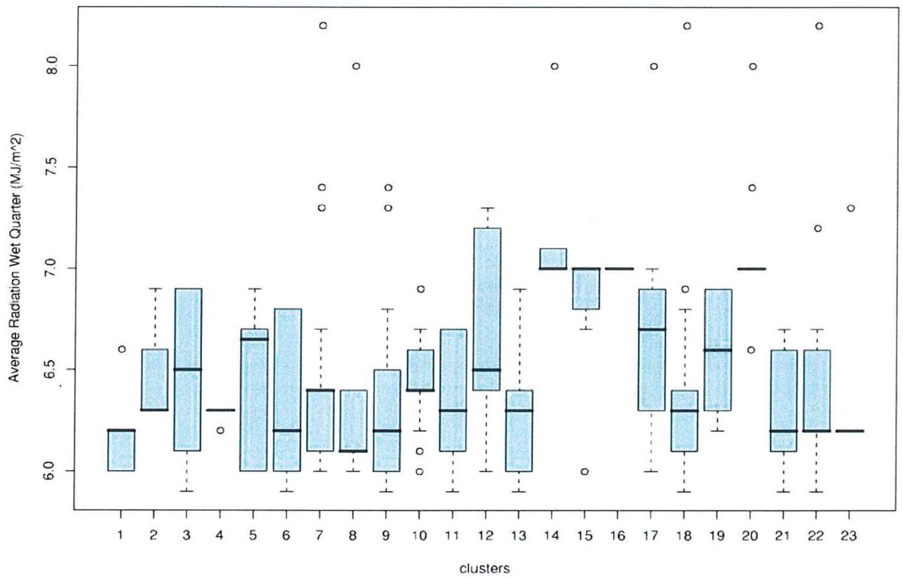

Figure 43

Boxplot showing the summary of the average radiation for the wettest quarter of the year for each cluster group.

Appendix 6

Table 1

Environmental variables, codes and units of measurement used in data analysis.

code	*definition*
VegType	Vegetation type. Ordinal productivity scale of 1 to 5.
Topo	Topography. Ordinal run-off regime scale of 1 to 7.
Cover	Vegetation cover. Percent cover.
Height	Vegetation height of dominant species. Expressed in metres
Geo	Geology immediately under soil pit. Ordinal fertility scale of 1 to 3.
Alt	Altitude in metres above sea level.
Burn	Burn frequency in an ordinal scale of 1 to 5.
TAP	Total annual precipitation in mm per annum.
DQ	Total precipitation during the driest quarter of the year in mm.
WQ	Total precipitation during the wettest quarter of the year in mm.
TARD	Total annual number of rain days.
TRDDQ	Total number of rain days for the driest quarter of the year.
TRDWQ	Total number of rain days for the driest quarter of the year.
TE	Total annual evaporation in mm.
TEDQ	Total evaporation in mm for the driest quarter of the year.
TEWQ	Total evaporation in mm for the wettest quarter of the year.

AvMinT	Average annual minimum temperature in degrees centigrade.
AveMaxT	Average annual maximum temperature in degrees centigrade.
MinTDQ	Minimum temperature, in degrees centigrade, of the driest quarter of the year.
MinTWQ	Minimum temperature, in degrees centigrade, of the wettest quarter of the year.
MaxTDQ	Maximum temperature, in degrees centigrade, of the driest quarter of the year.
MaxTWQ	Maximum temperature, in degrees centigrade, of the wettest quarter of the year.
AveRA	Average annual radiation in MJ.
AveRadDQ	Average radiation in MJ for the driest quarter of the year.
AveRAdWQ	Average radiation in MJ for the wettest quarter of the year.

Appendix 7

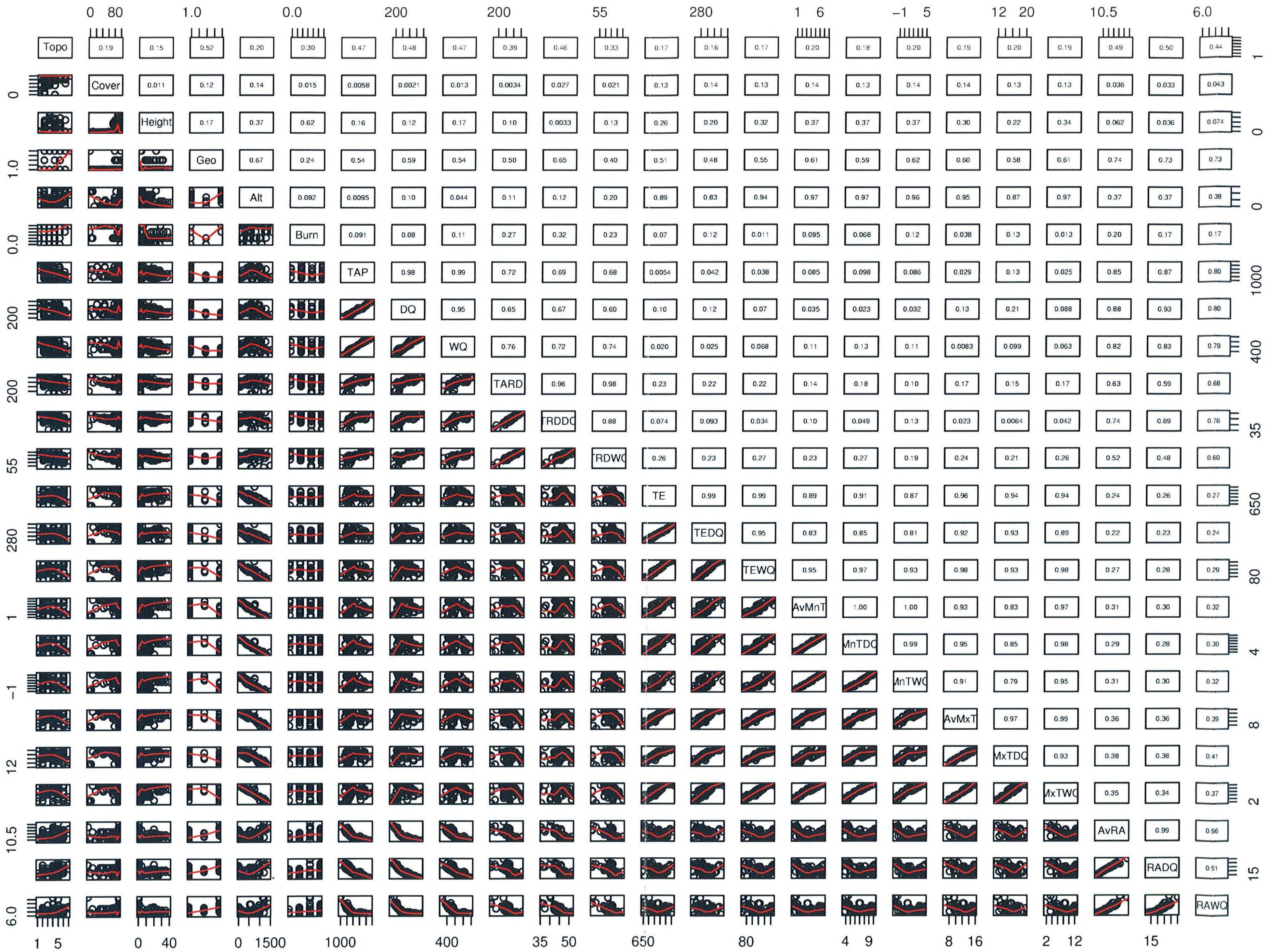

Figure 1

Pairwise plot of environmental factors described in Chapters 3 and 4. Spearman's rank correlation co-efficient provided in the upper section of the plot.

Table 1

AIC agreement of the 23 unsupervised clusters when a reduced set of environmental factors are used to predict the unsupervised clusters as described in Chapter 4.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	30	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	11	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	17	0	0	0	0	0	0	5	0	0	3	0	0	0	0	0	0	0	0	0	0
4	1	0	0	19	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	0	31	5	1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	4	24	1	0	7	0	1	0	0	0	0	0	0	0	0	0	1	0	3
7	0	0	0	0	0	4	13	6	30	1	0	3	0	0	0	0	3	0	0	0	3	1	0
8	0	0	0	0	0	2	0	15	3	0	0	0	0	0	0	0	1	3	0	0	5	0	0
9	0	0	0	0	0	4	6	4	46	4	0	10	0	0	0	0	7	6	0	0	5	0	0
10	9	0	3	0	6	0	1	0	0	44	3	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	1	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	2	1	0	0	0	0	25	9	0	0	0	0	2	0	0	1	1	0
13	0	0	2	0	0	0	0	0	0	5	0	0	57	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	37	1	0	0	0	0	12	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	1	0	40	0	0	1	0	0	1	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	20	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	8	19	0	1	0	5	0
18	0	0	0	0	0	8	1	0	11	0	0	0	0	0	0	0	3	84	0	0	1	4	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	20	1	1	0	0
20	0	0	0	0	0	0	0	0	1	0	0	0	0	13	0	0	0	0	0	22	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	4	51	1	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	14	0	0	8	68	0
23	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	10	10

Appendix 8

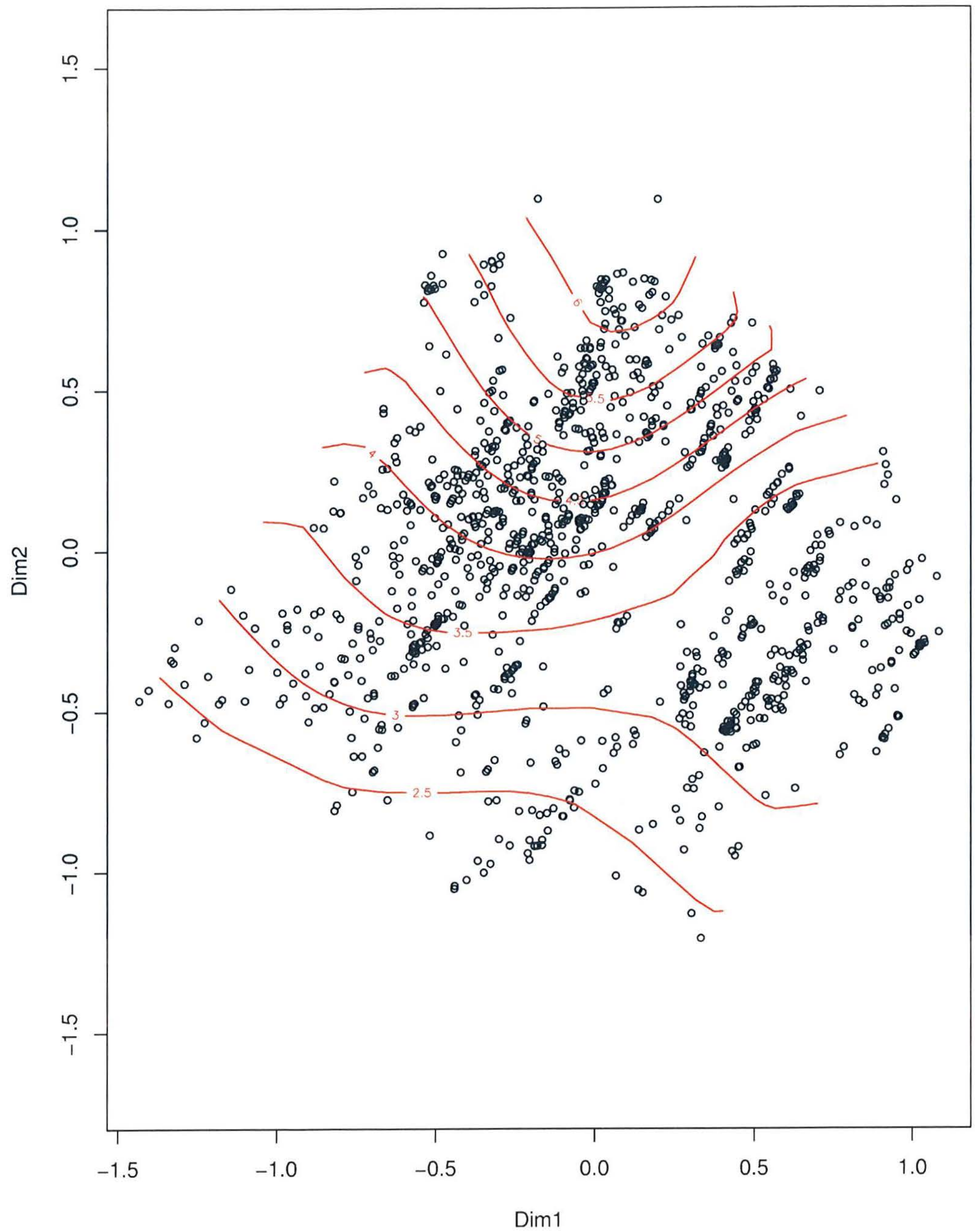

Figure 1

Thinplate spline smoothing contours overlay on ordination plot. Red lines show topography classes described in the methods section of Chapter 4.

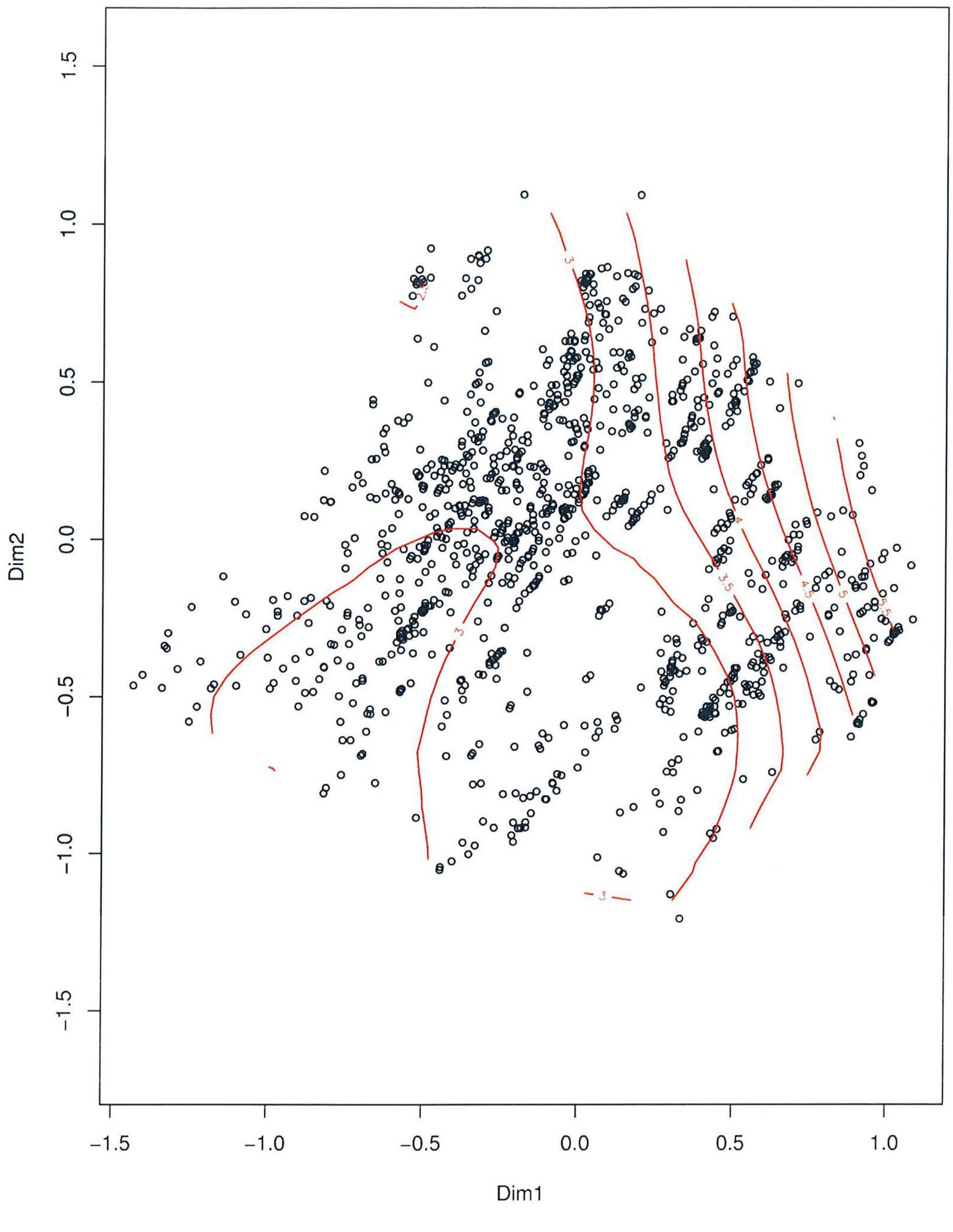

Figure 2

Thinplate spline smoothing contours overlay on ordination plot. Red lines show vegetation type classes described in the methods section of Chapter 4.

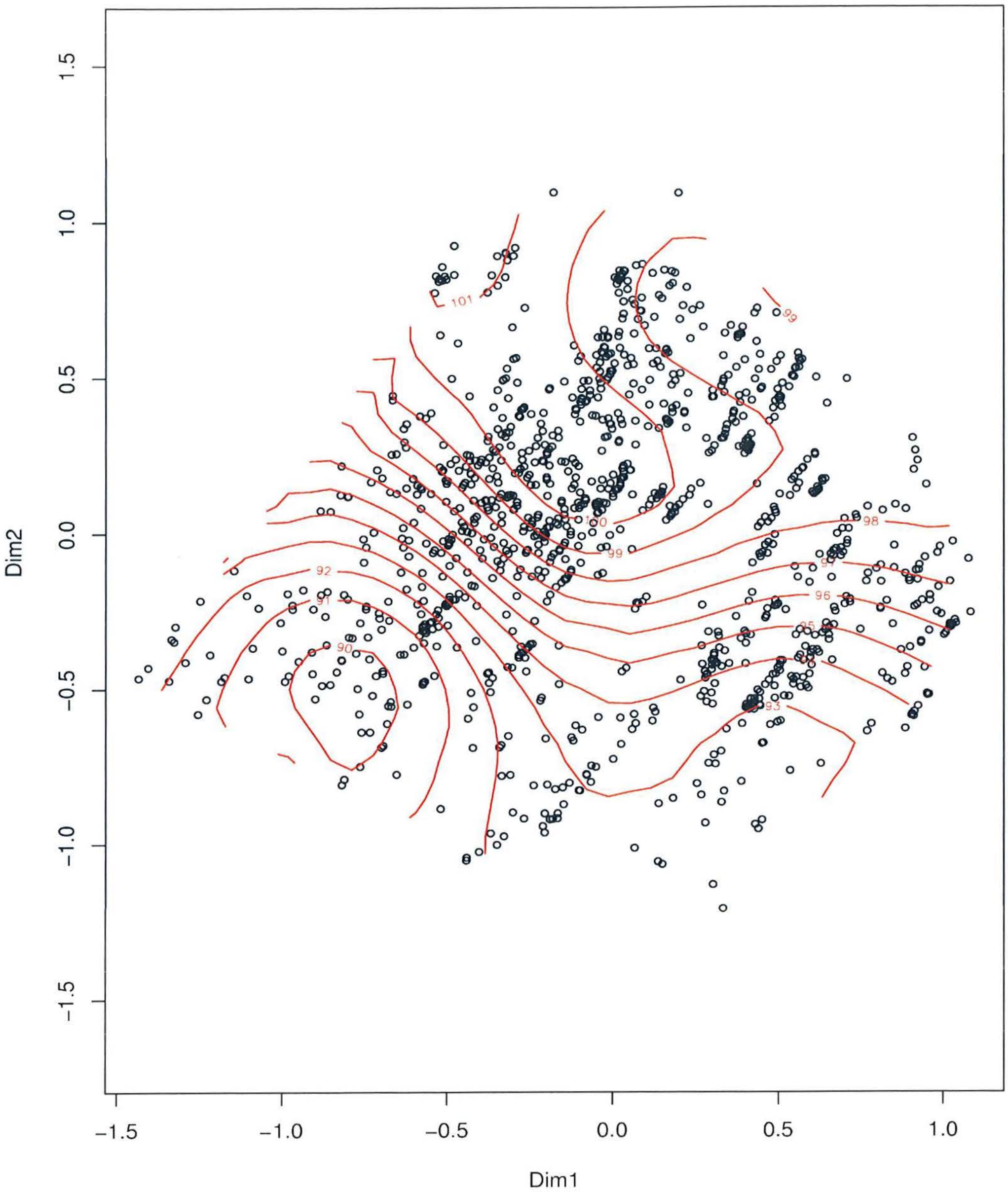

Figure 3

Thinplate spline smoothing contours overlay on ordination plot. Red lines show vegetation cover percentage described in the methods section of Chapter 4.

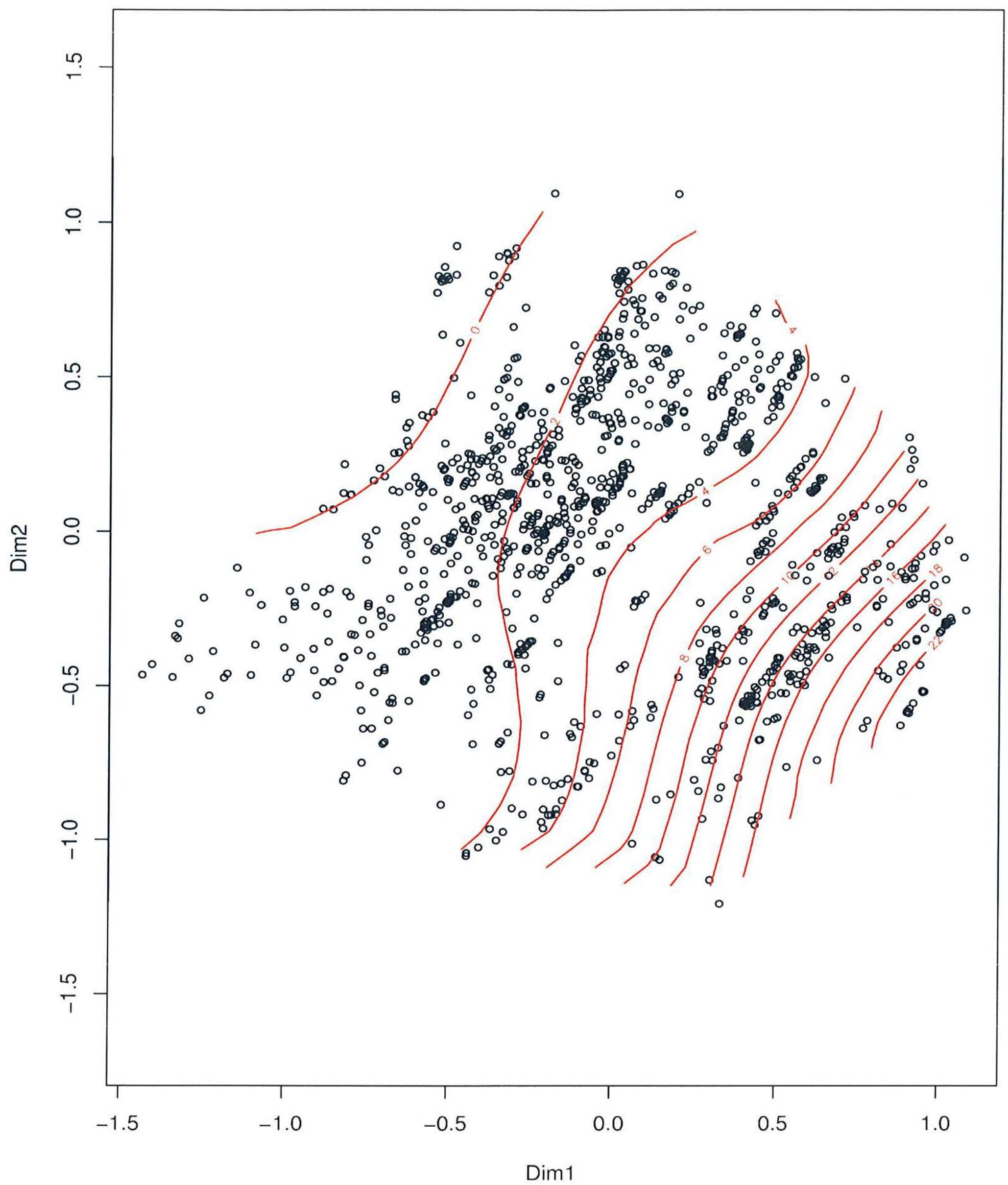

Figure 4

Thinplate spline smoothing contours overlay on ordination plot. Red lines show vegetation height in metres described in the methods section of Chapter 4.

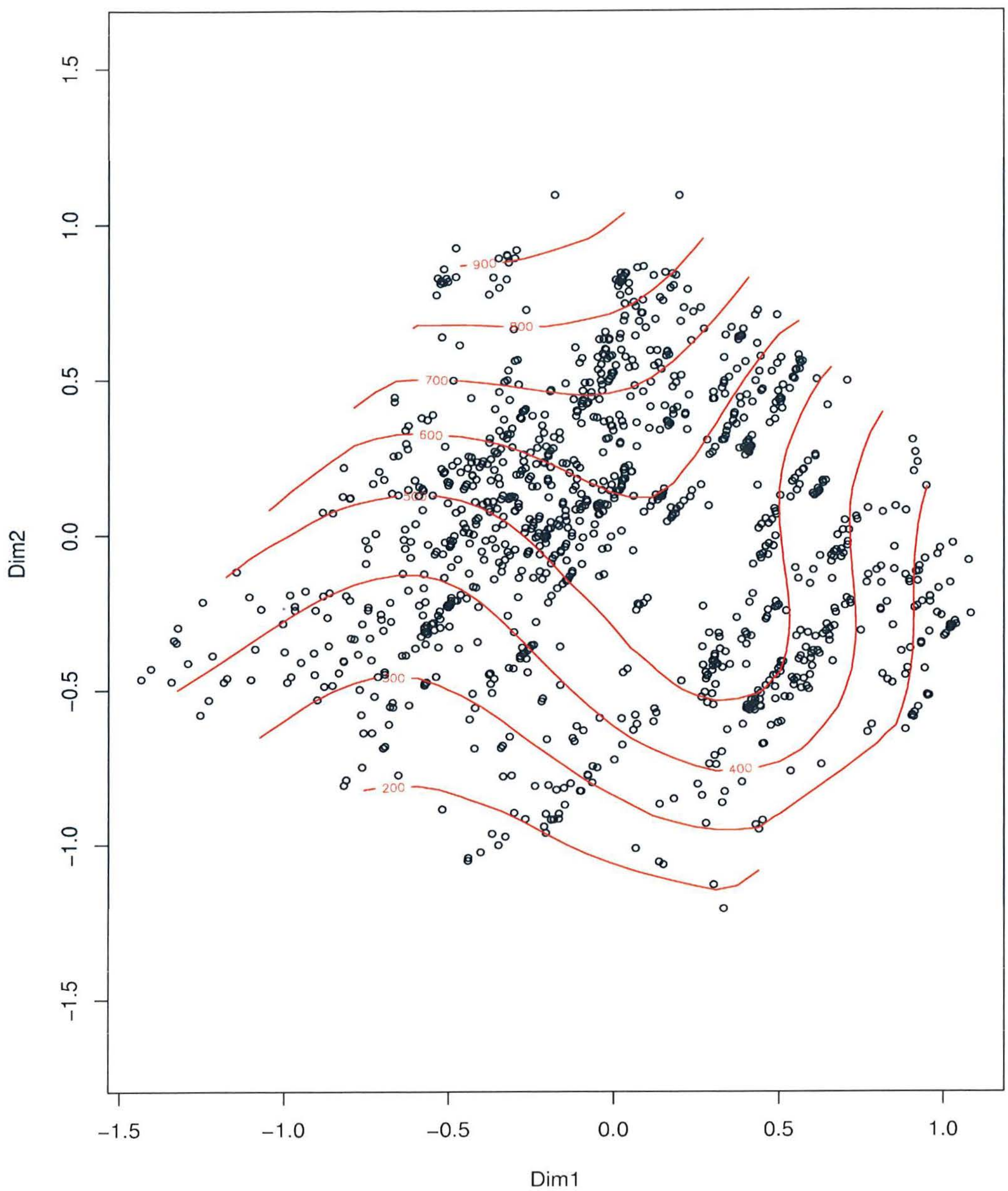

Figure 5

Thinplate spline smoothing contours overlay on ordination plot. Red lines show altitude in m a.s.l. described in the methods section of Chapter 4.

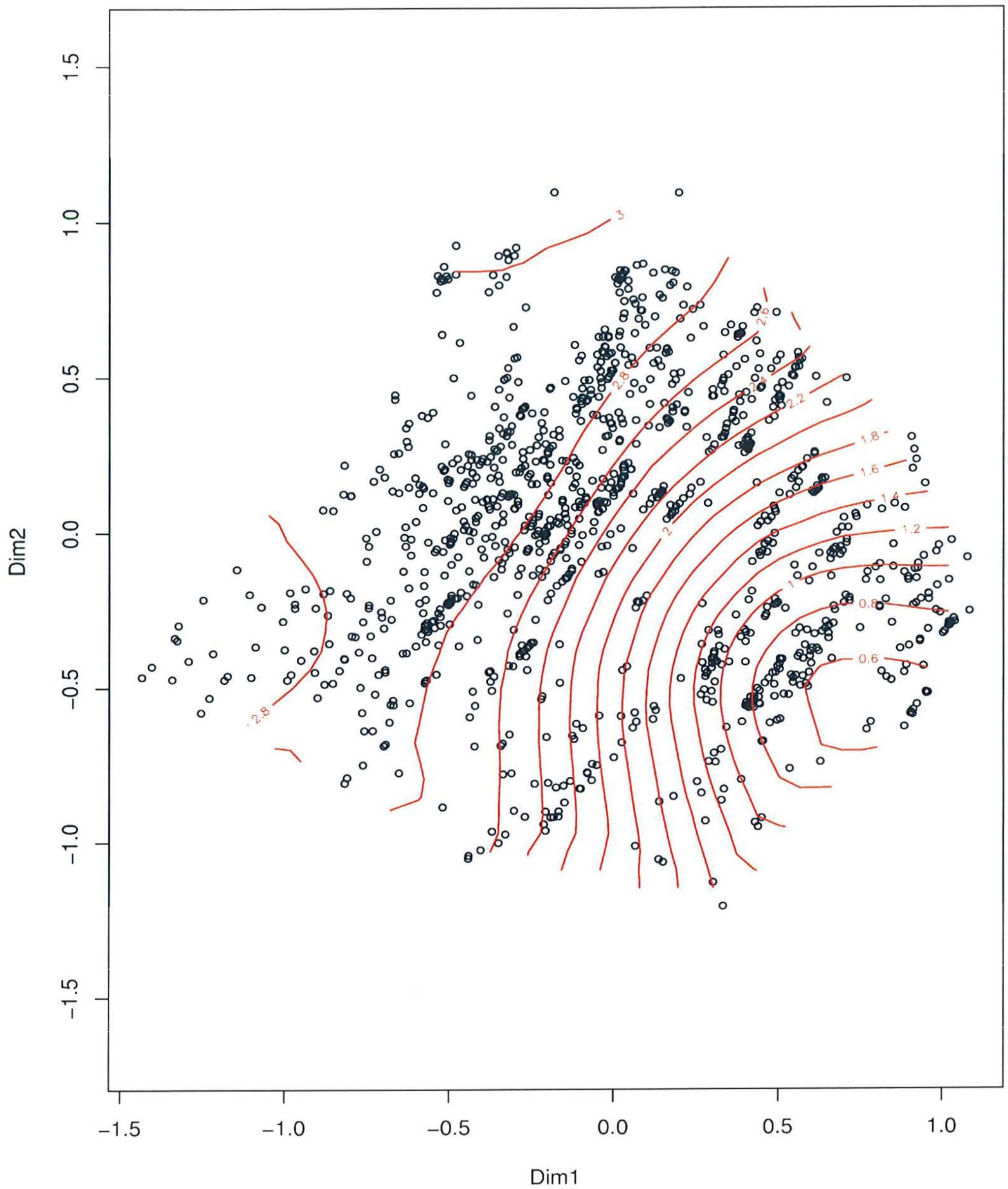

Figure 6

Thinplate spline smoothing contours overlay on ordination plot. Red lines show burn frequency as described in the methods section of Chapter 4.

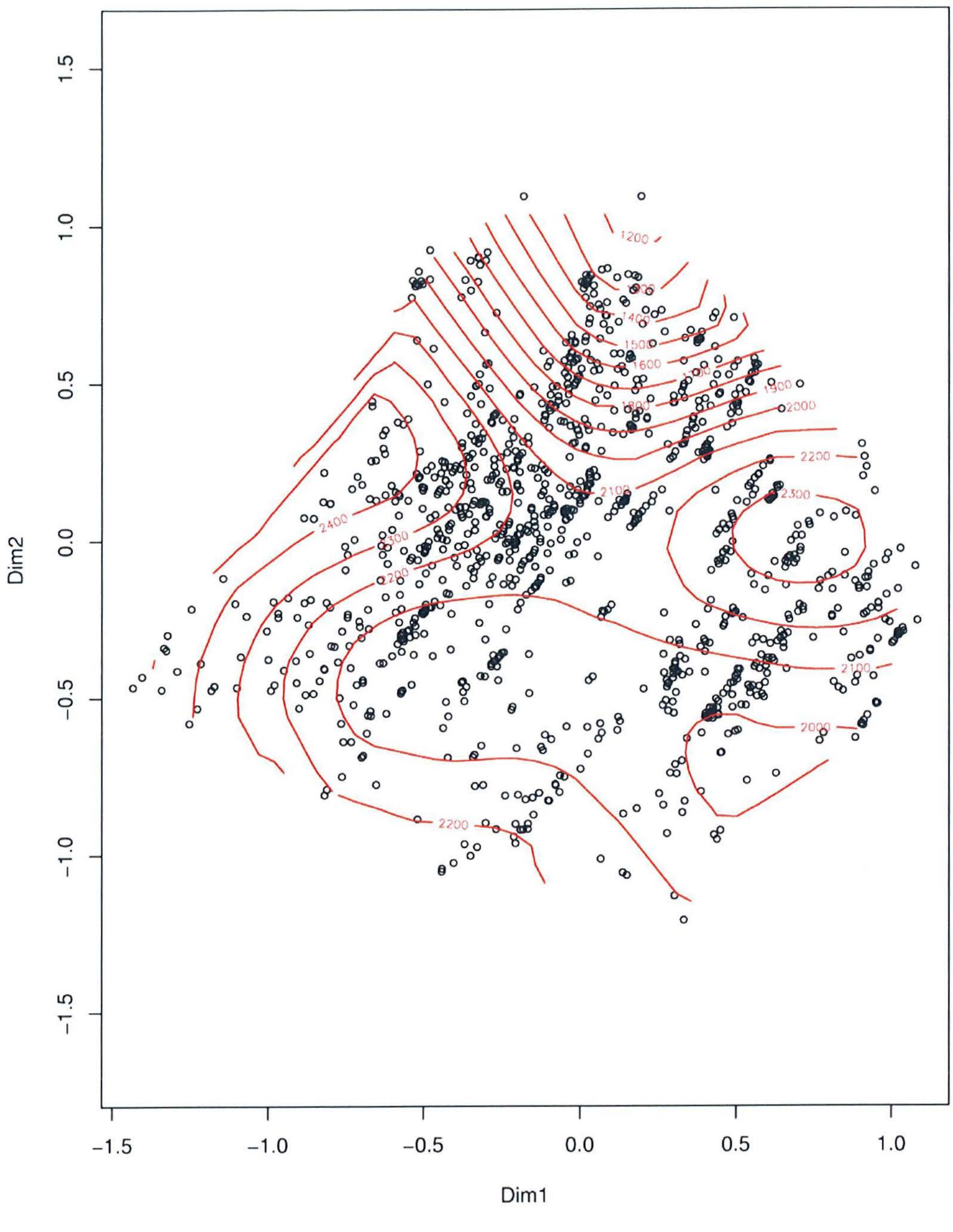

Figure 7

Thinplate spline smoothing contours overlay on ordination plot. Red lines total annual precipitation in mm as described in the methods section of Chapter 4.

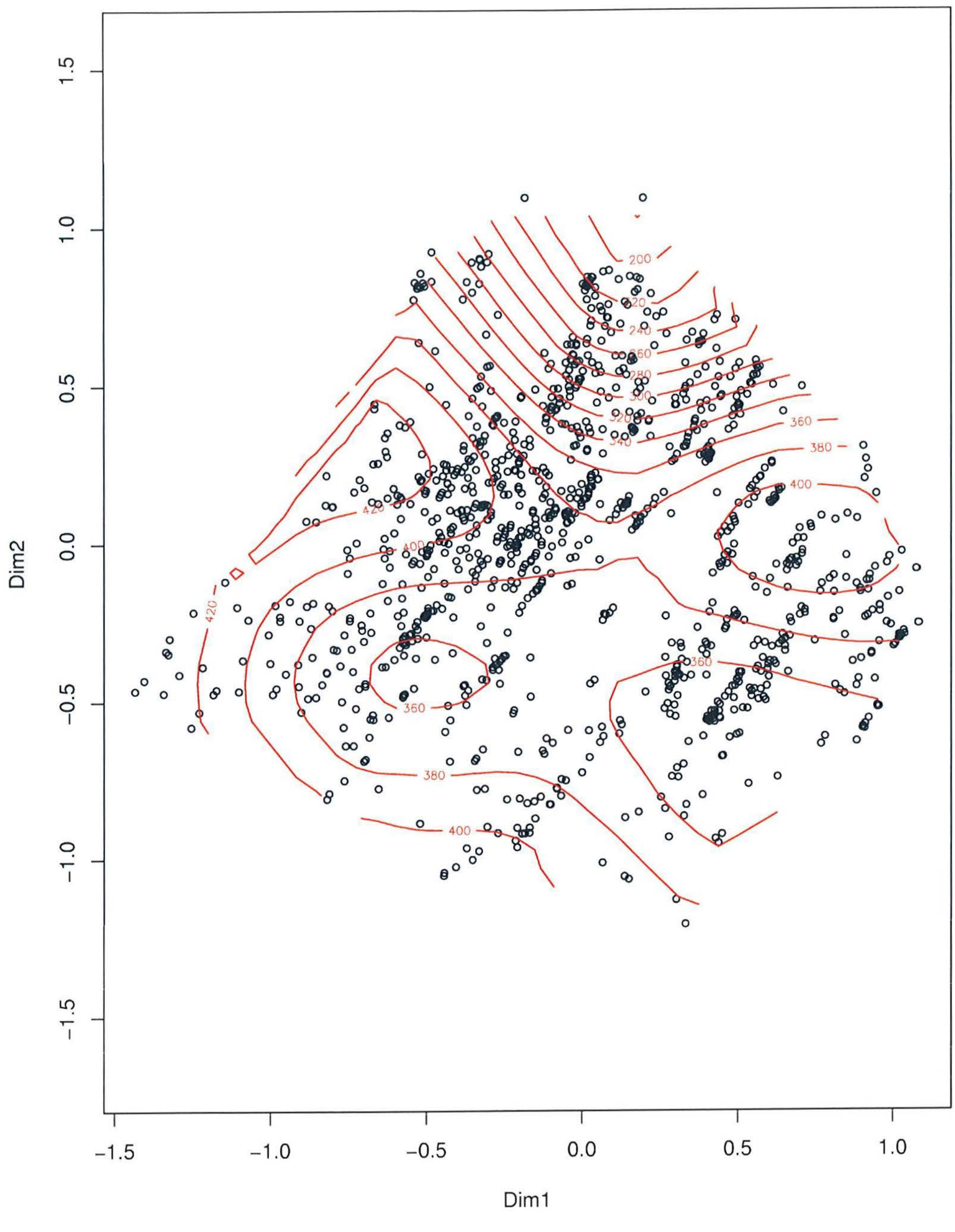

Figure 8

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total precipitation during the driest quarter of the year in mm as described in the methods section of Chapter 4.

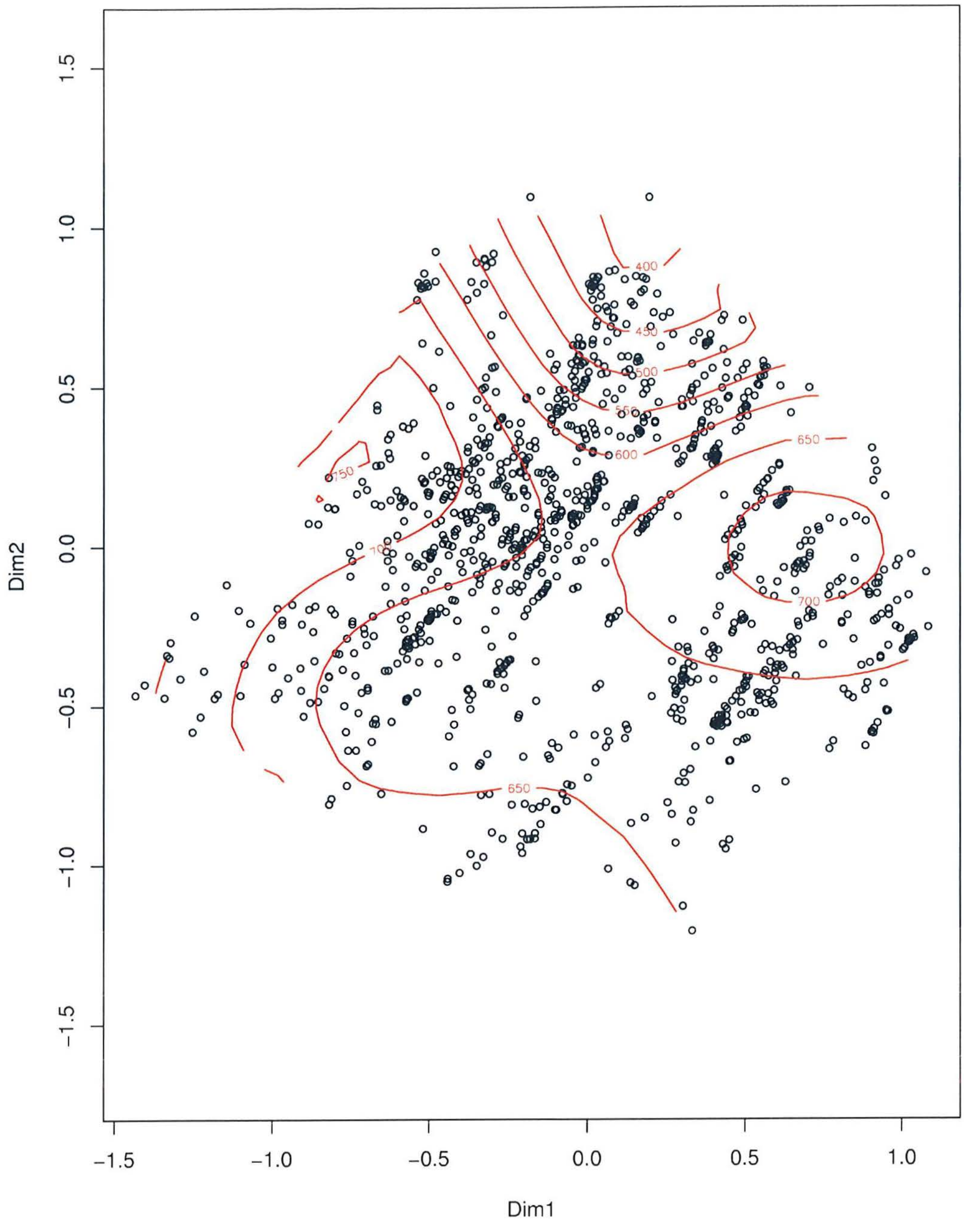

Figure 9

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total precipitation during the wettest quarter of the year in mm as described in the methods section of Chapter 4.

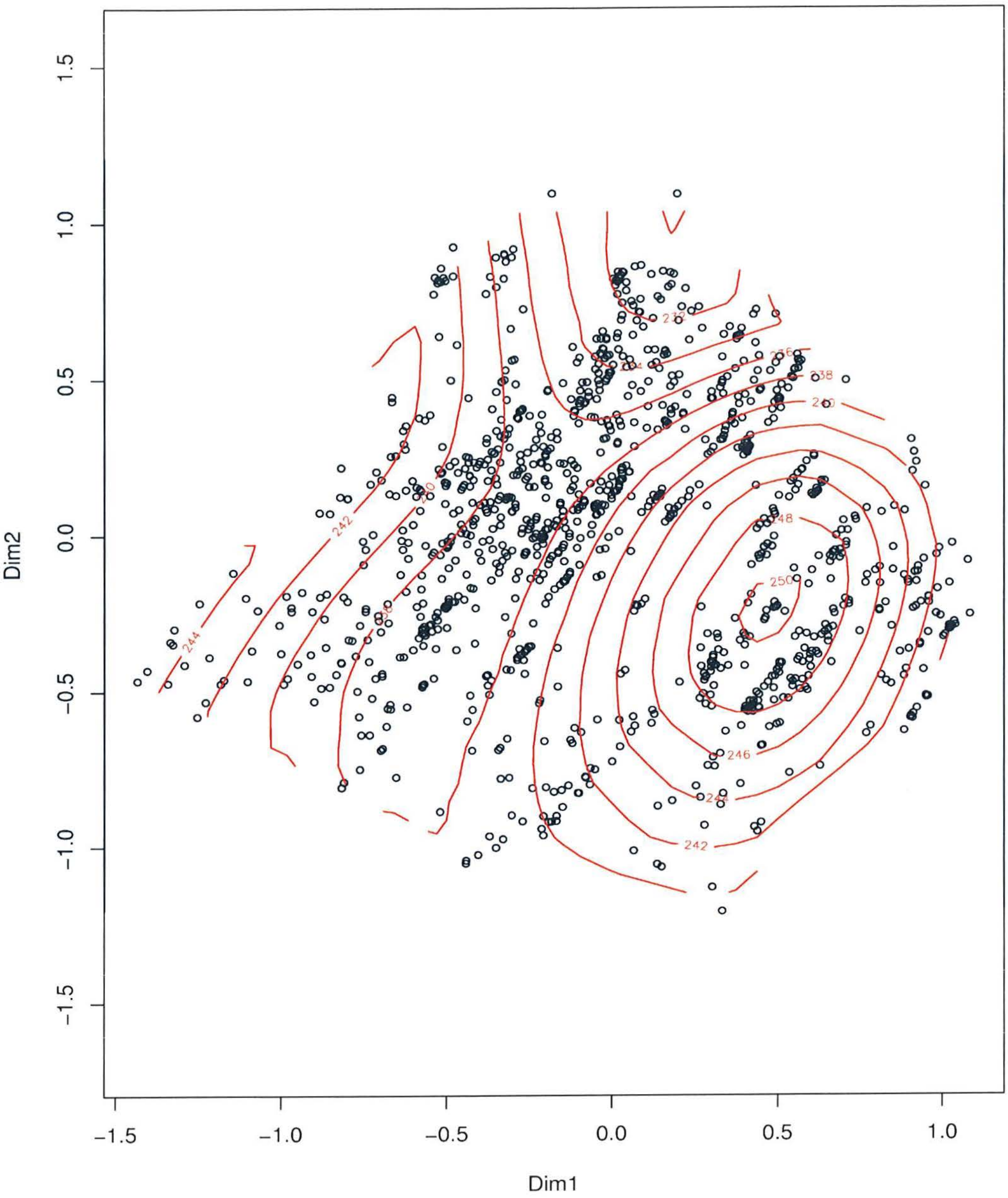

Figure 10

Thinplate spline smoothing contours overlay on ordination plot. Red lines show the total annual rain days as described in the methods section of Chapter 4.

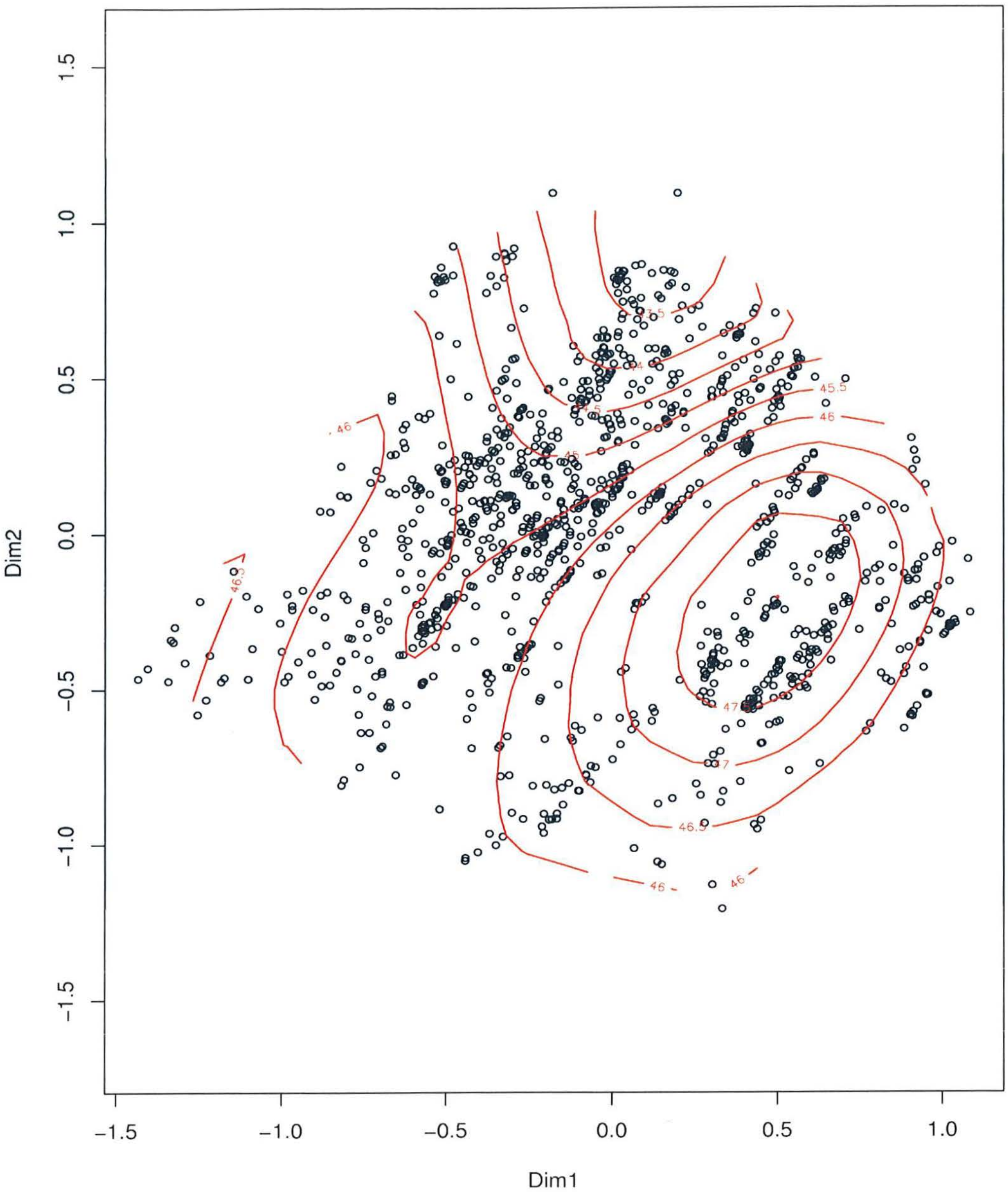

Figure 11

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total rain days during the driest quarter of the year as described in the methods section of Chapter 4.

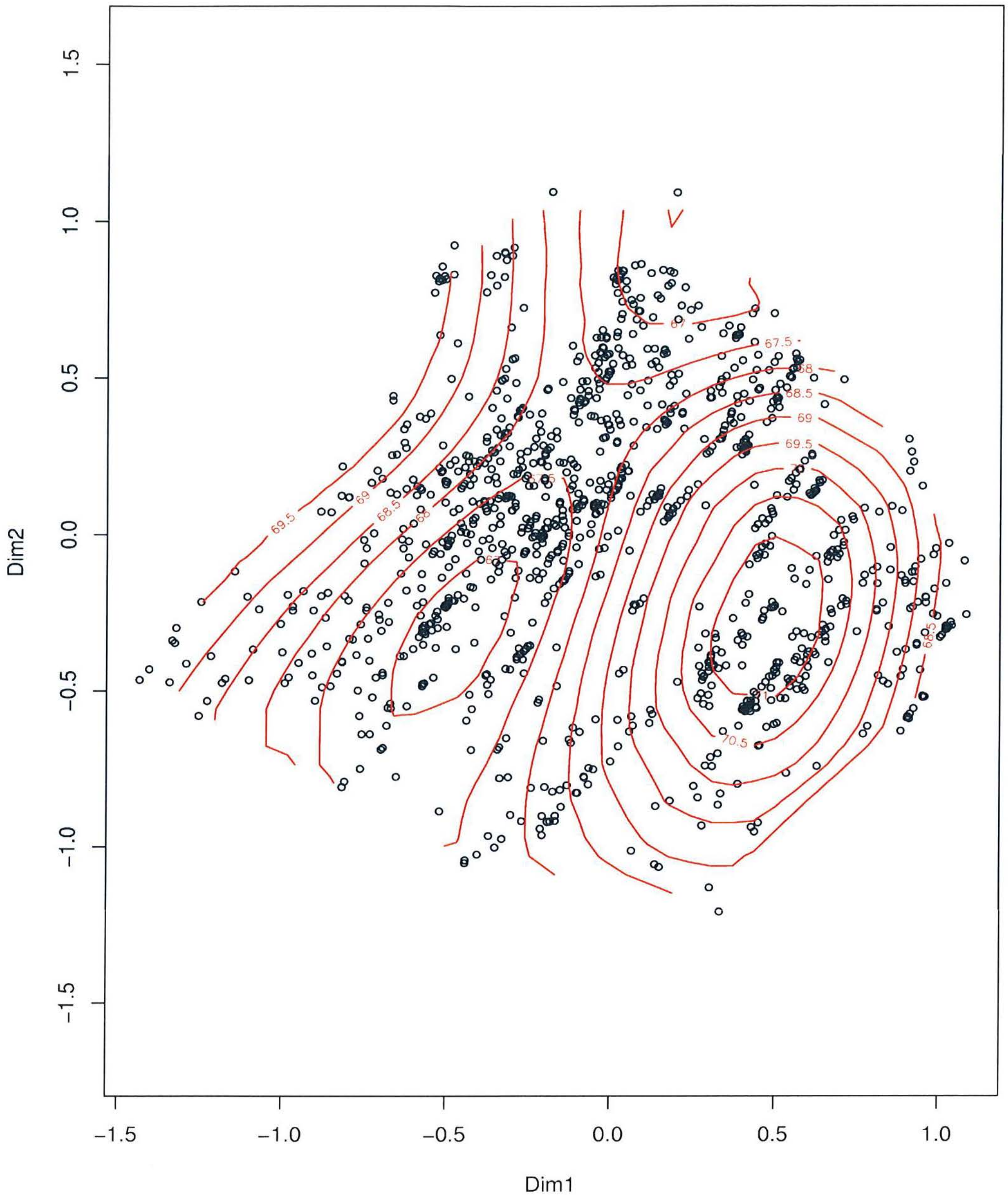

Figure 12

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total rain days during the wettest quarter of the year as described in the methods section of Chapter 4.

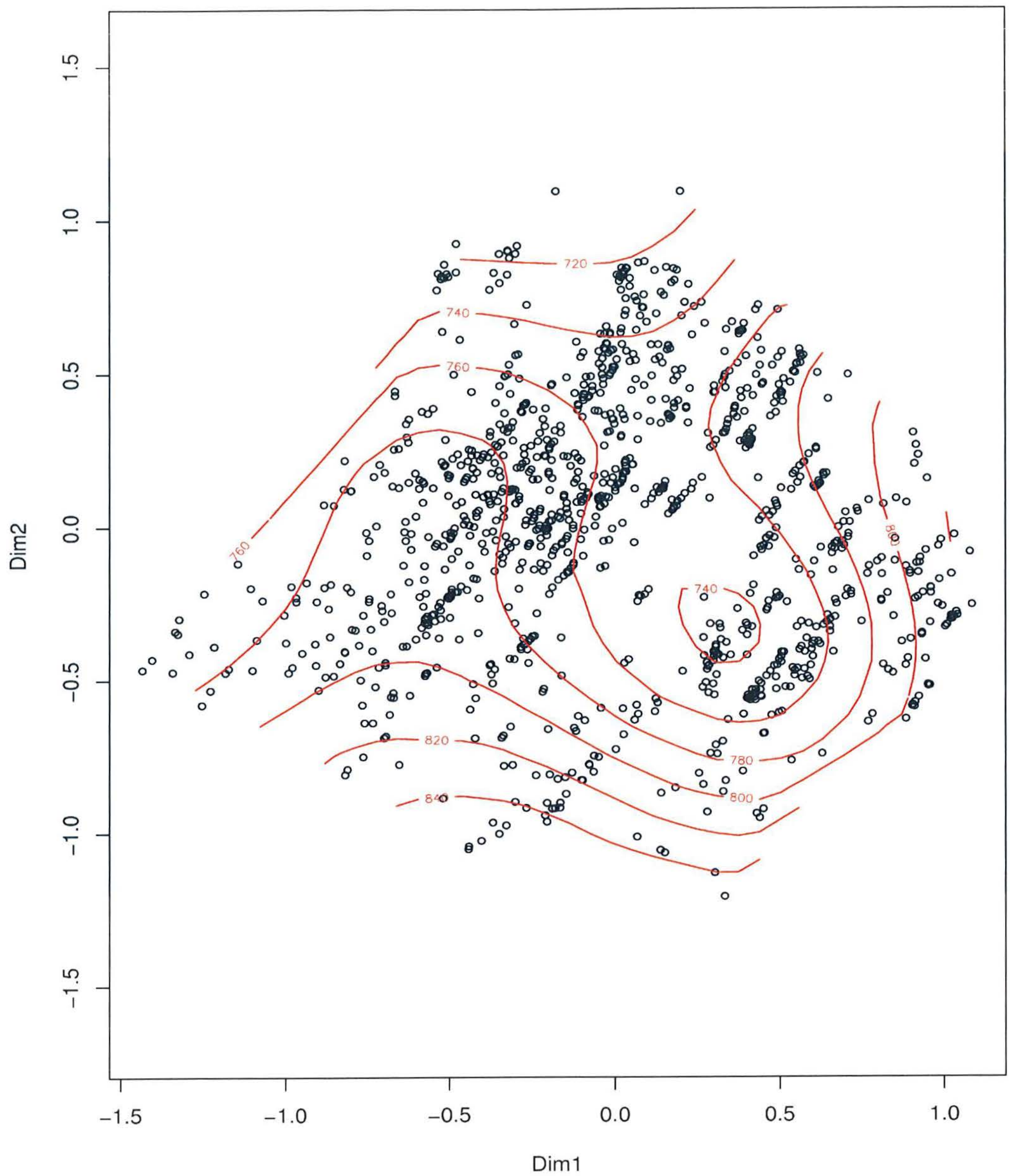

Figure 13

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total annual evaporation in mm as described in the methods section of Chapter 4.

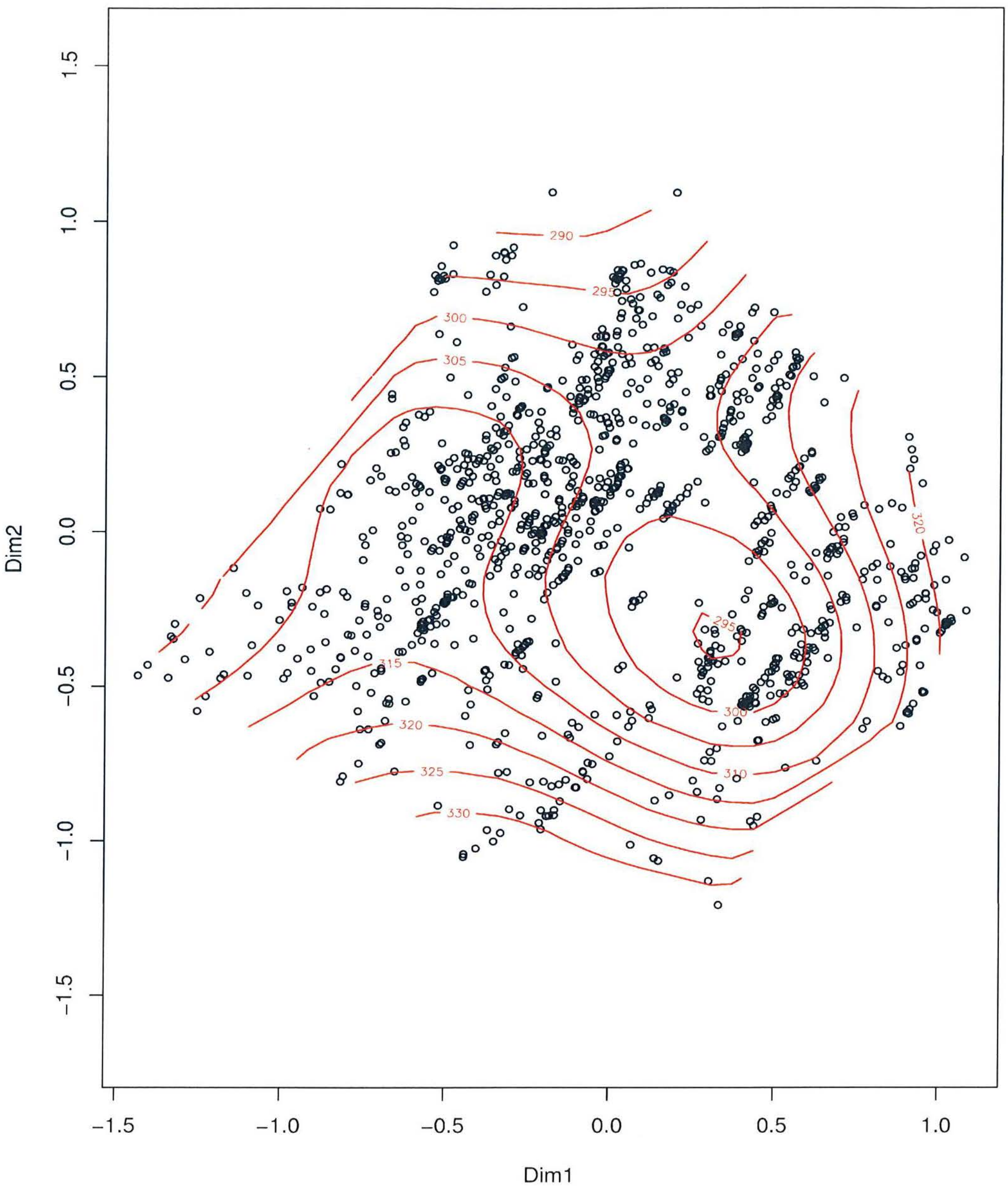

Figure 14

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total evaporation during the driest quarter of the year in mm as described in the methods section of Chapter 4.

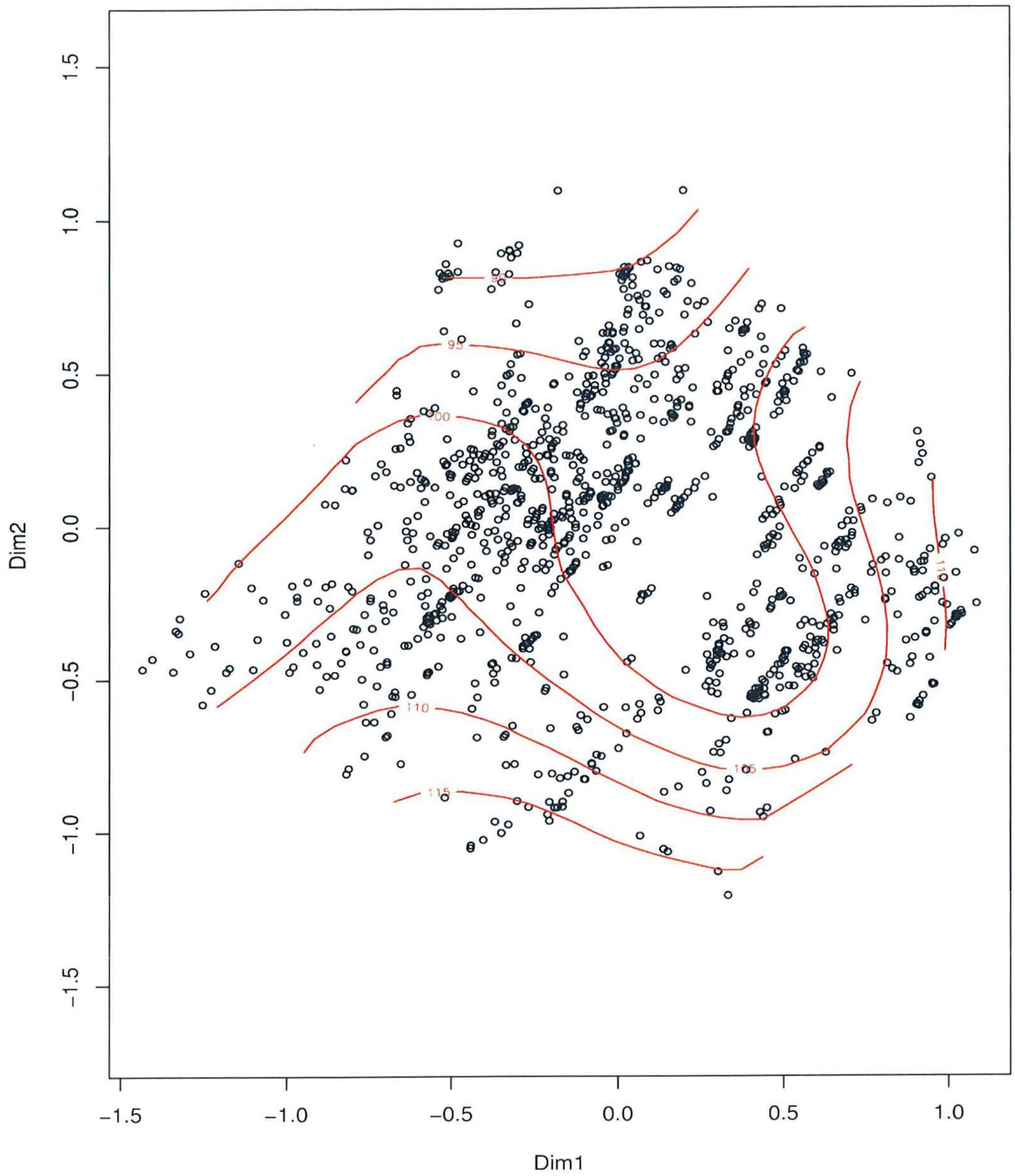

Figure 15

Thinplate spline smoothing contours overlay on ordination plot. Red lines show total evaporation during the wettest quarter of the year in mm as described in the methods section of Chapter 4.

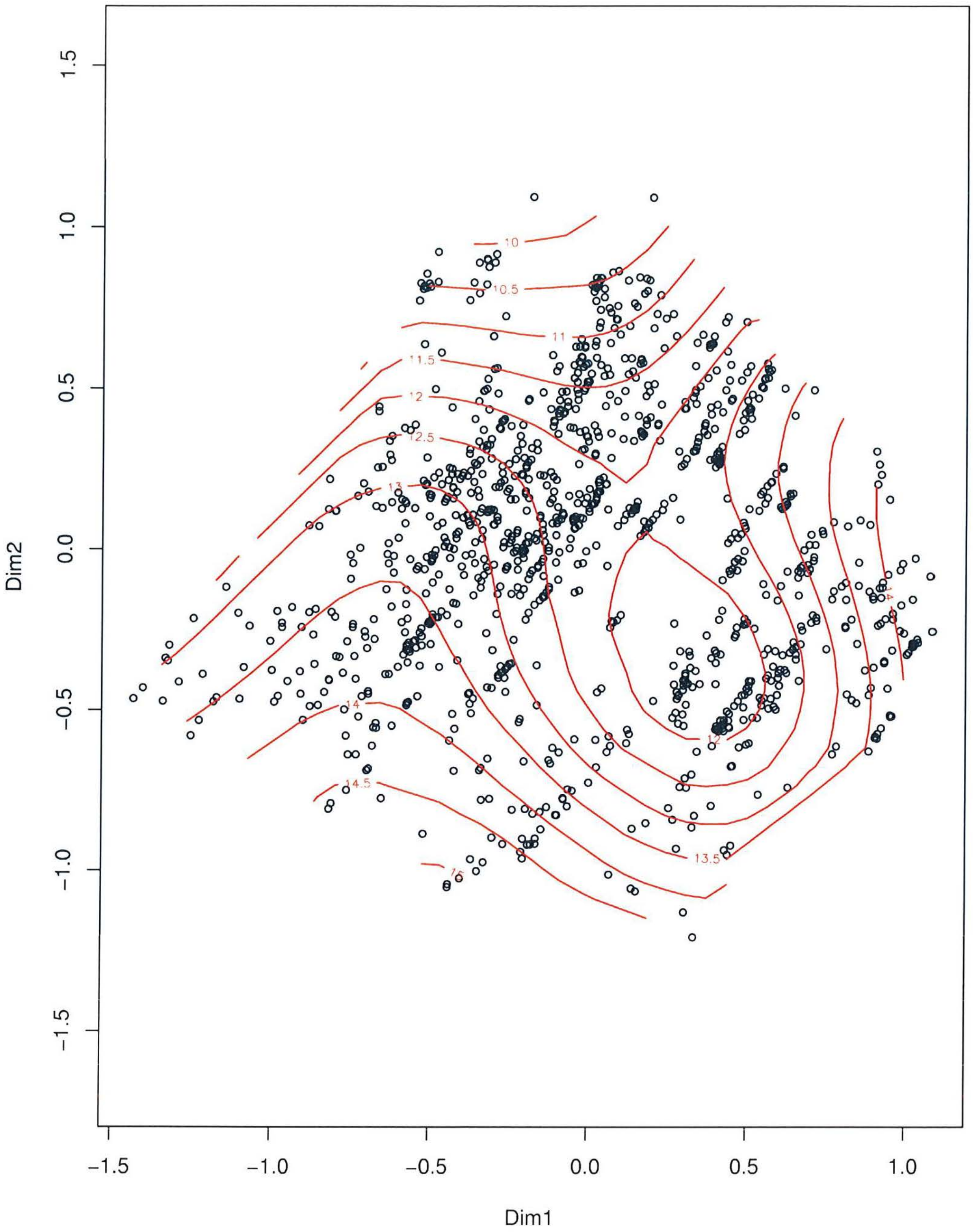

Figure 16

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average maximum temperature in °C as described in the methods section of Chapter 4.

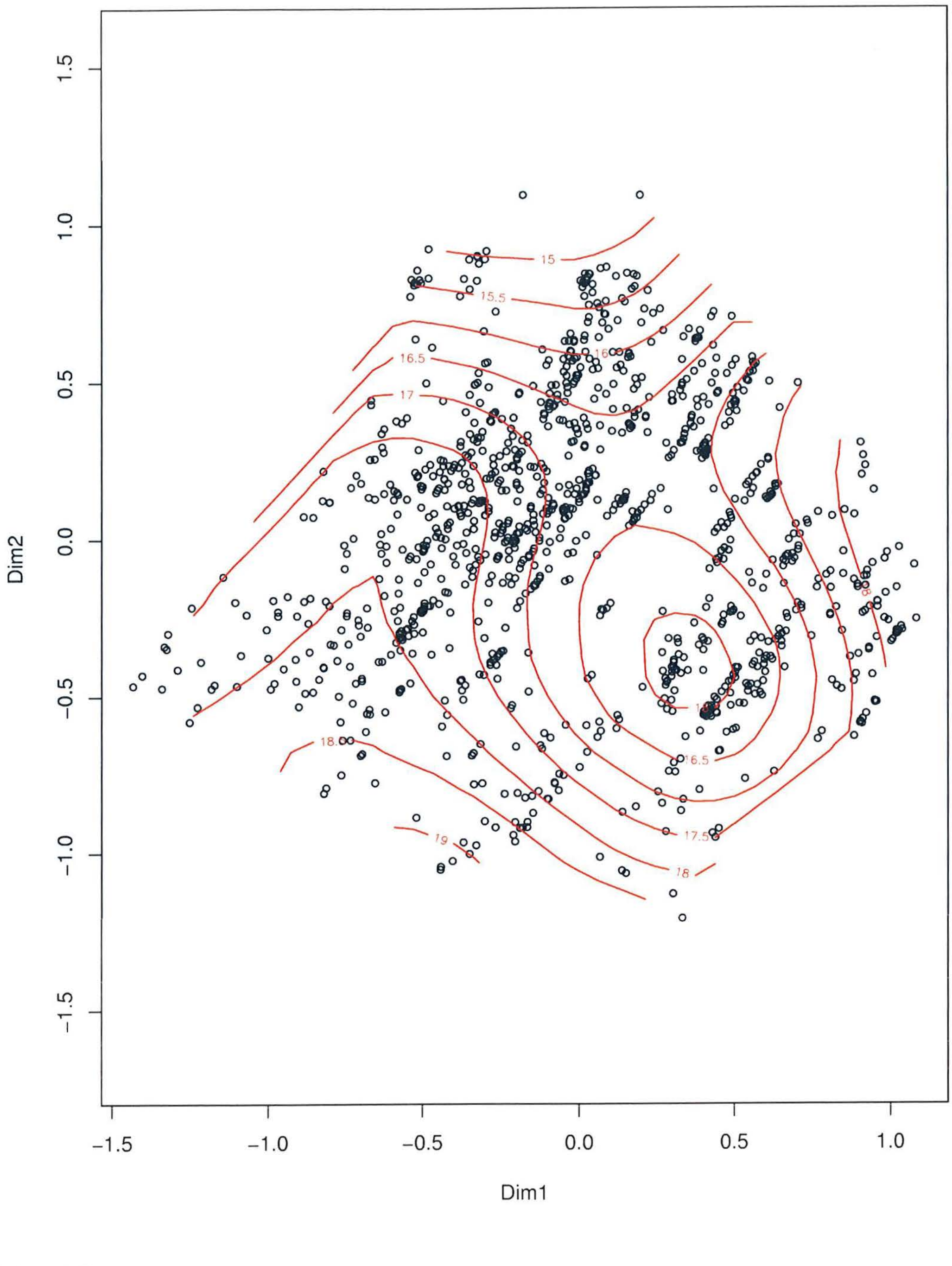

Figure 17

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average maximum temperature during the driest quarter of the year in °C as described in the methods section of Chapter 4.

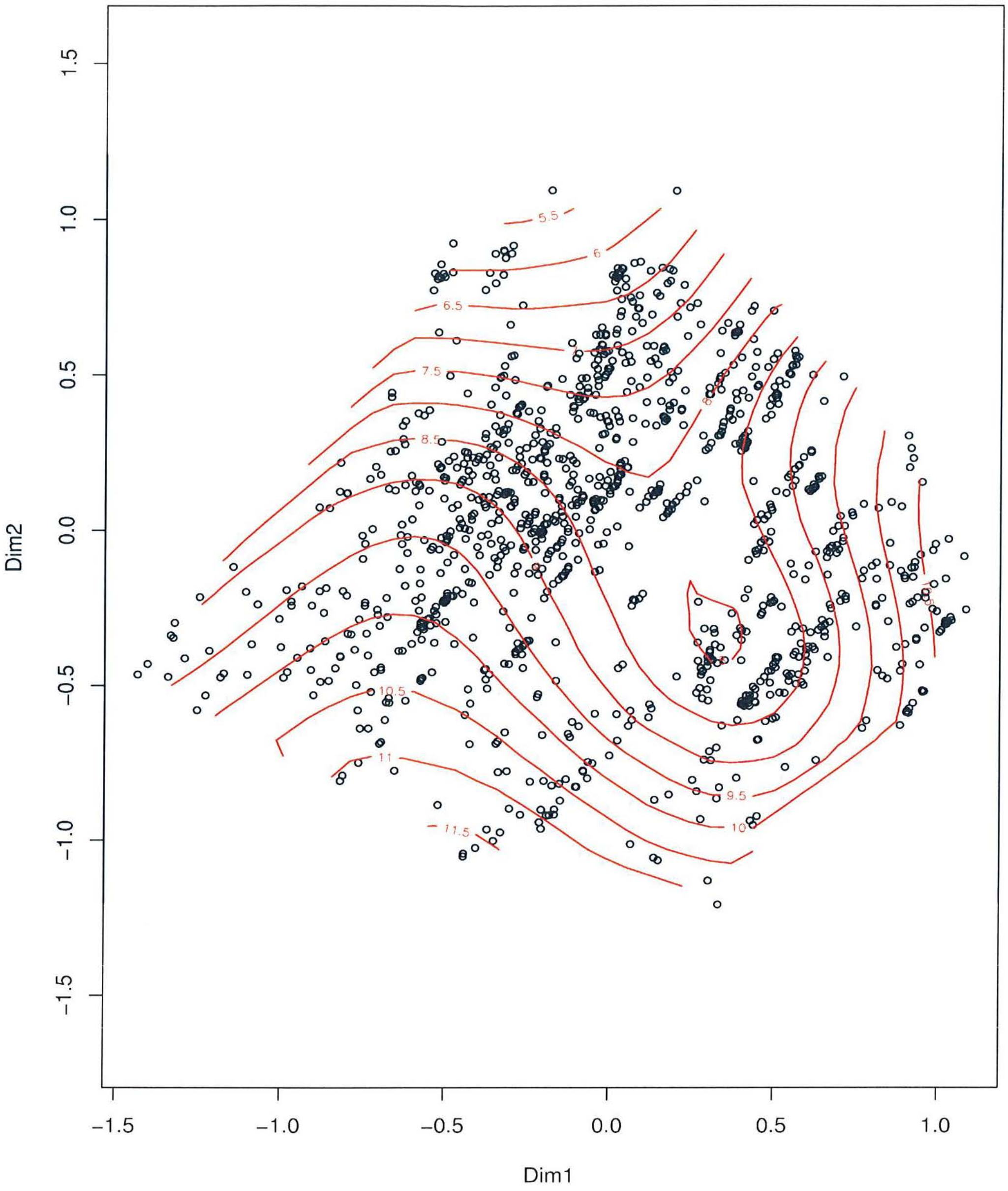

Figure 18

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average maximum temperature during the wettest quarter of the year in °C as described in the methods section of Chapter 4.

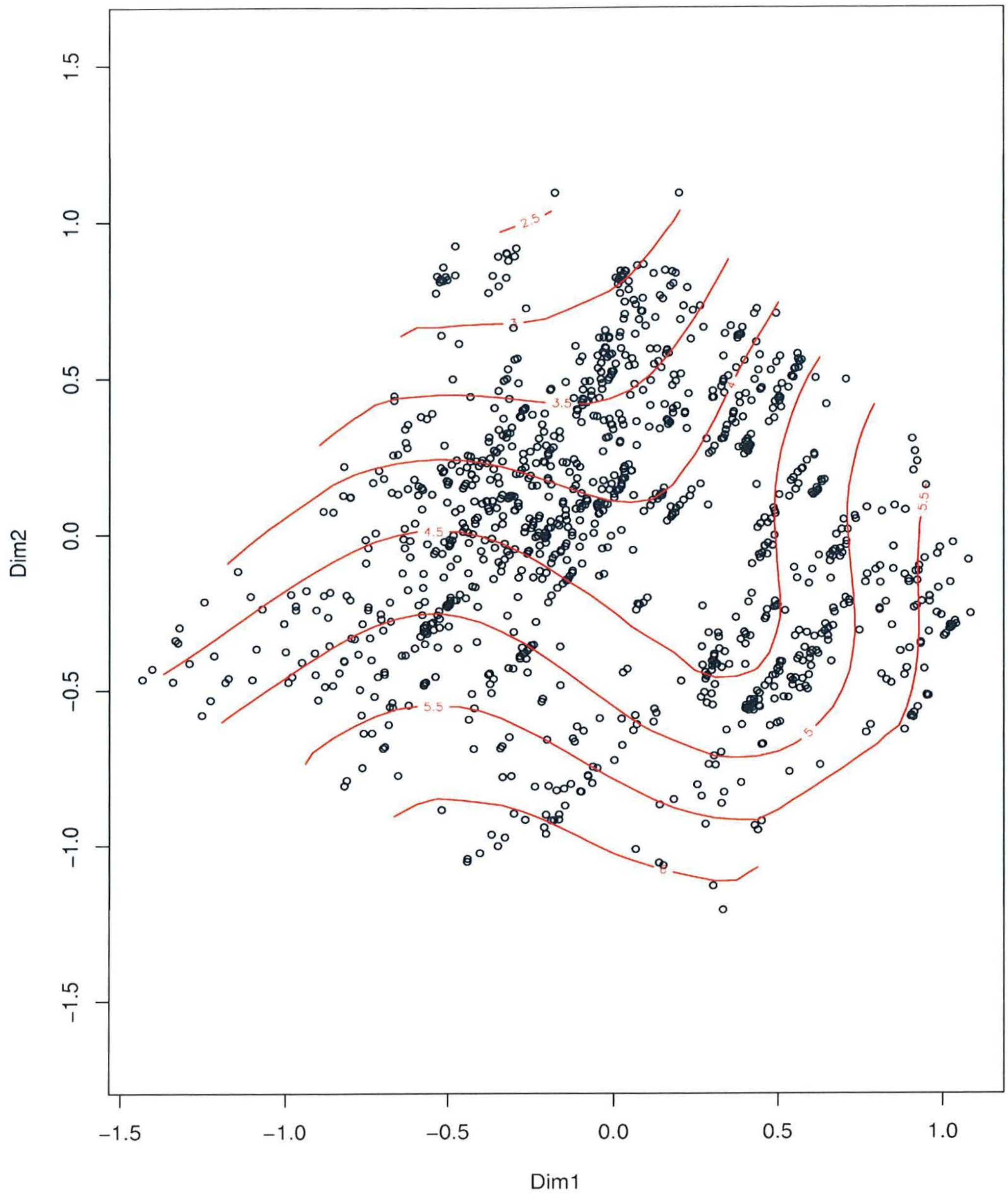

Figure 19

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average annual minimum temperature in °C as described in the methods section of Chapter 4.

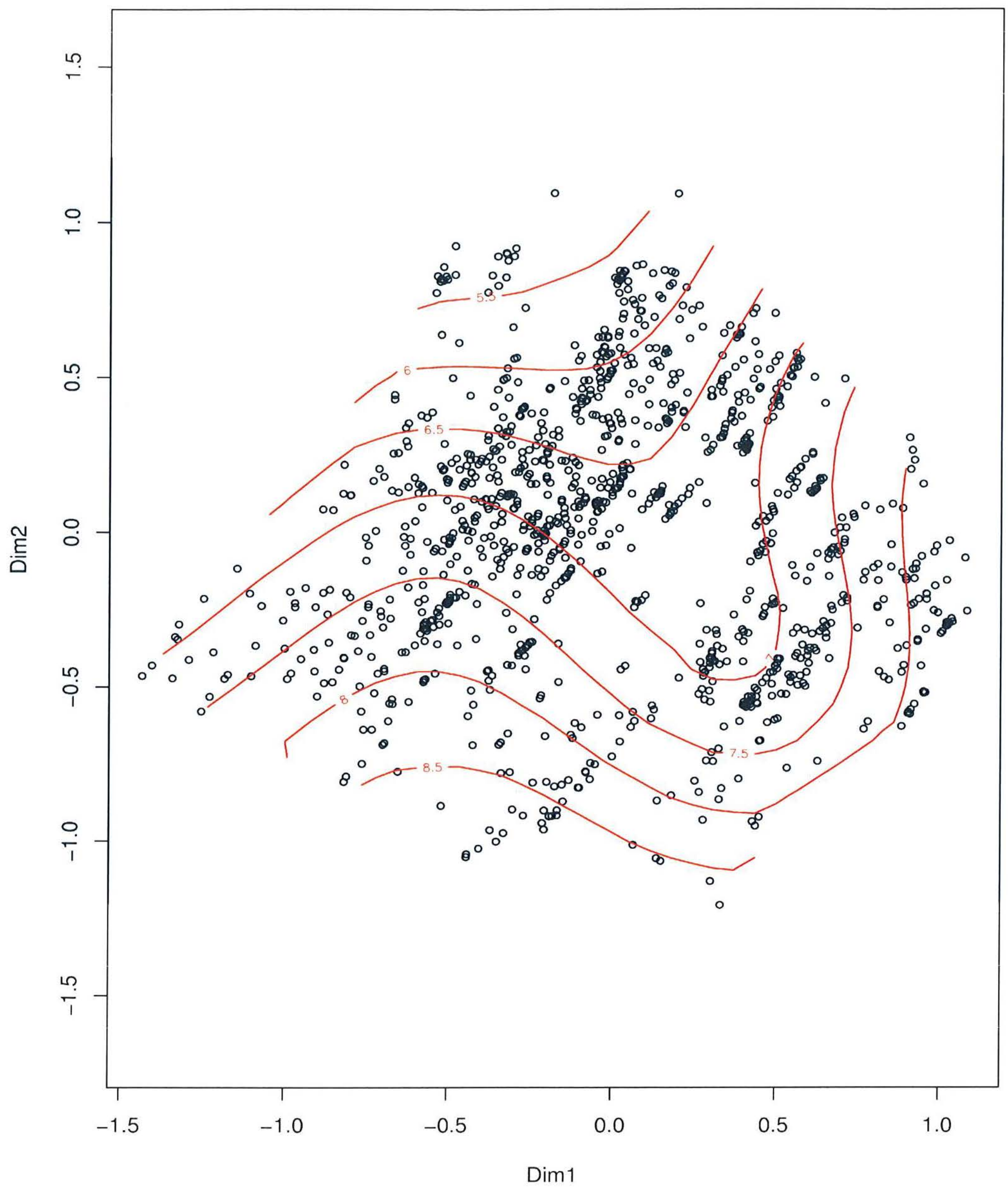

Figure 20

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average minimum temperature during the driest quarter of the year in °C as described in the methods section of Chapter 4.

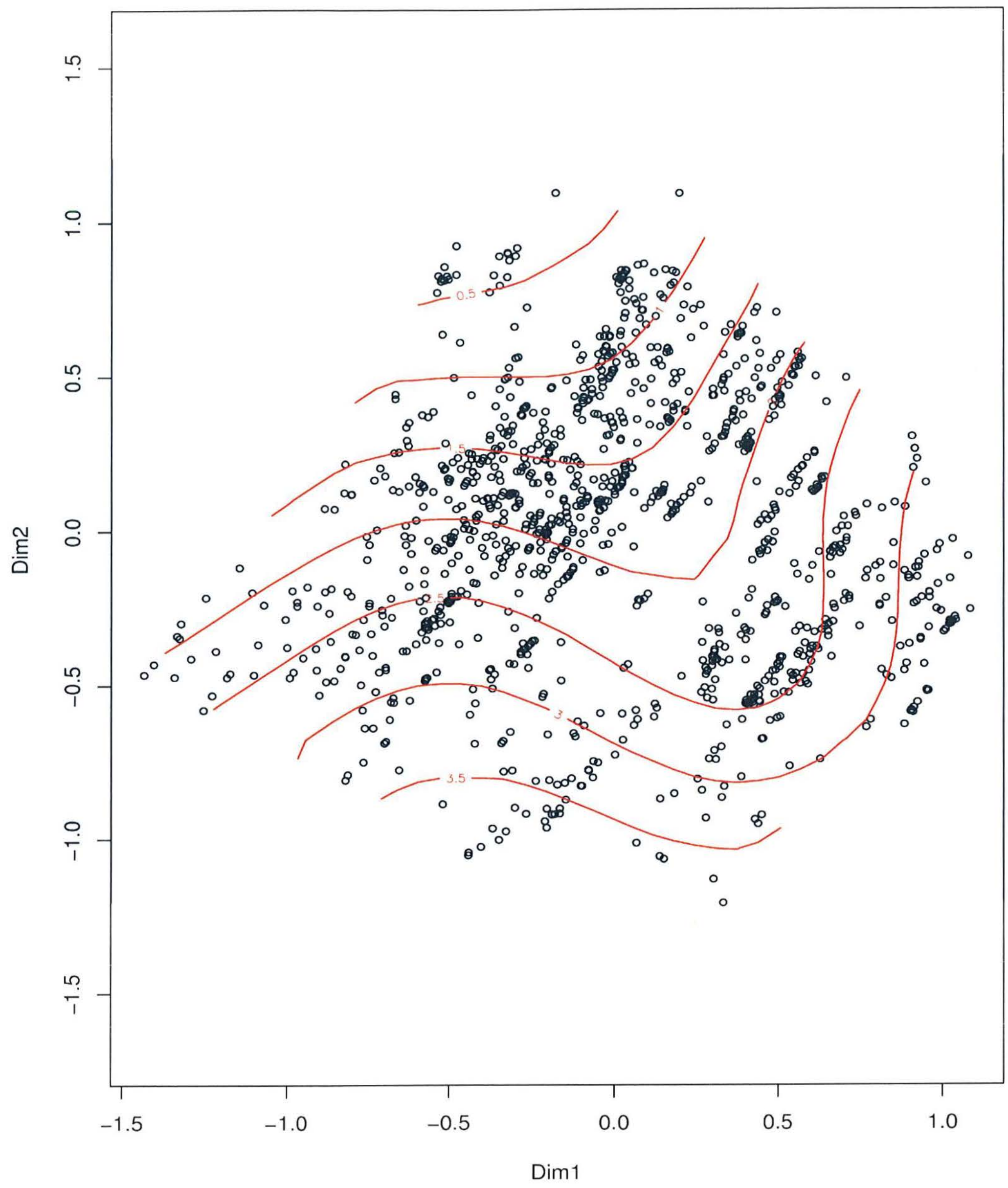

Figure 21

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average minimum temperature during the wettest quarter of the year in °C as described in the methods section of Chapter 4.

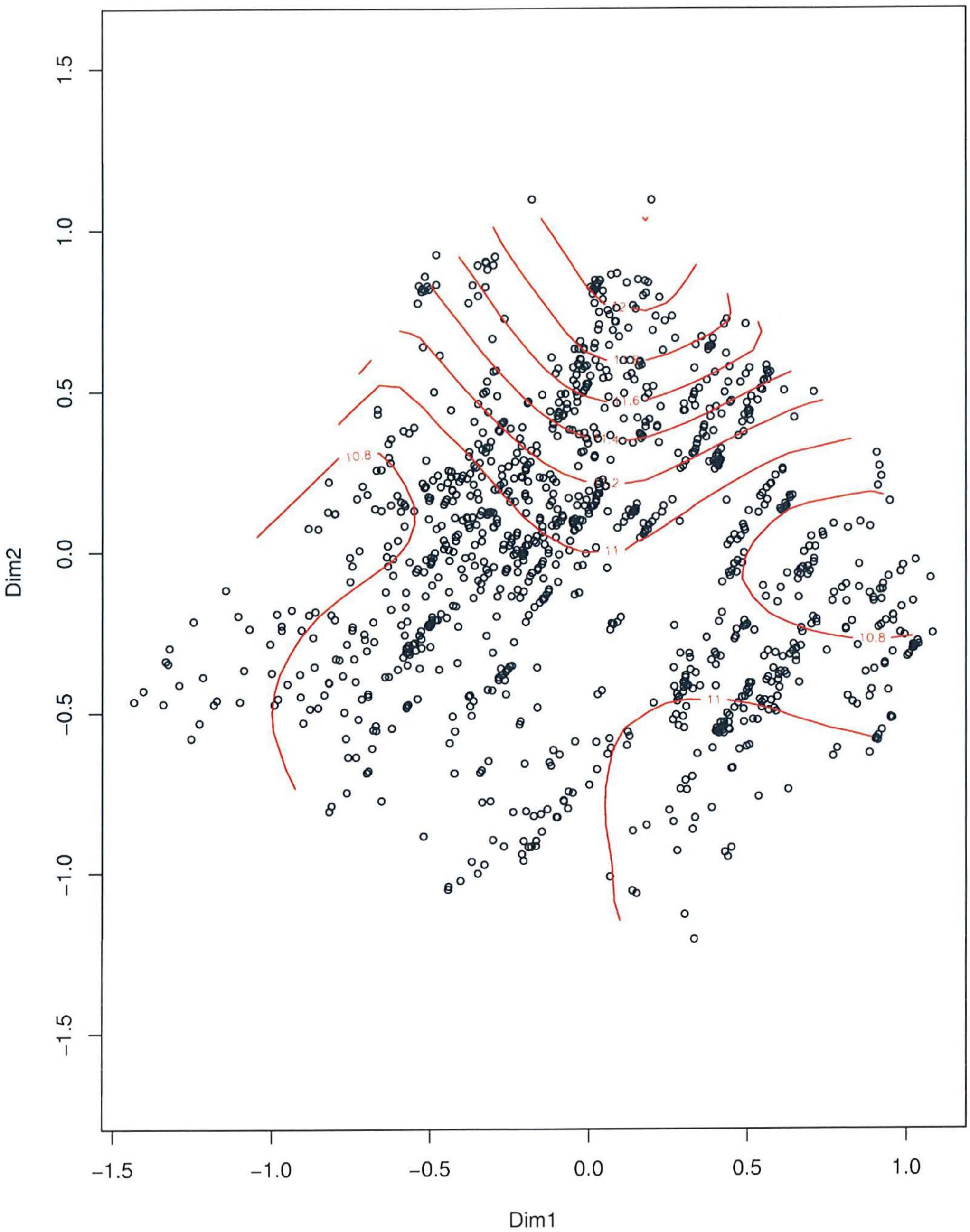

Figure 22

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average radiation as described in the methods section of Chapter 4.

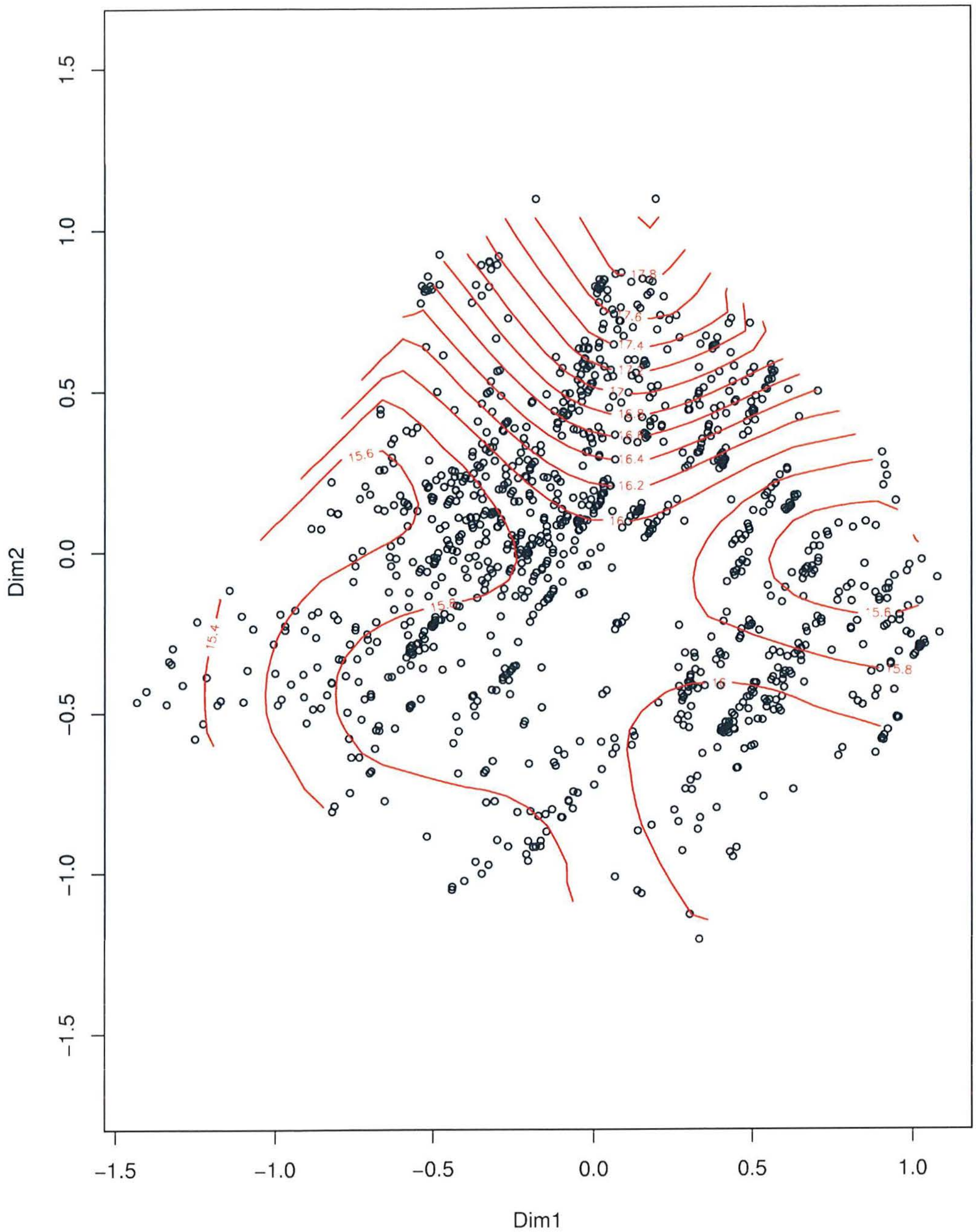

Figure 23

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average radiation during the driest quarter of the year as described in the methods section of Chapter 4.

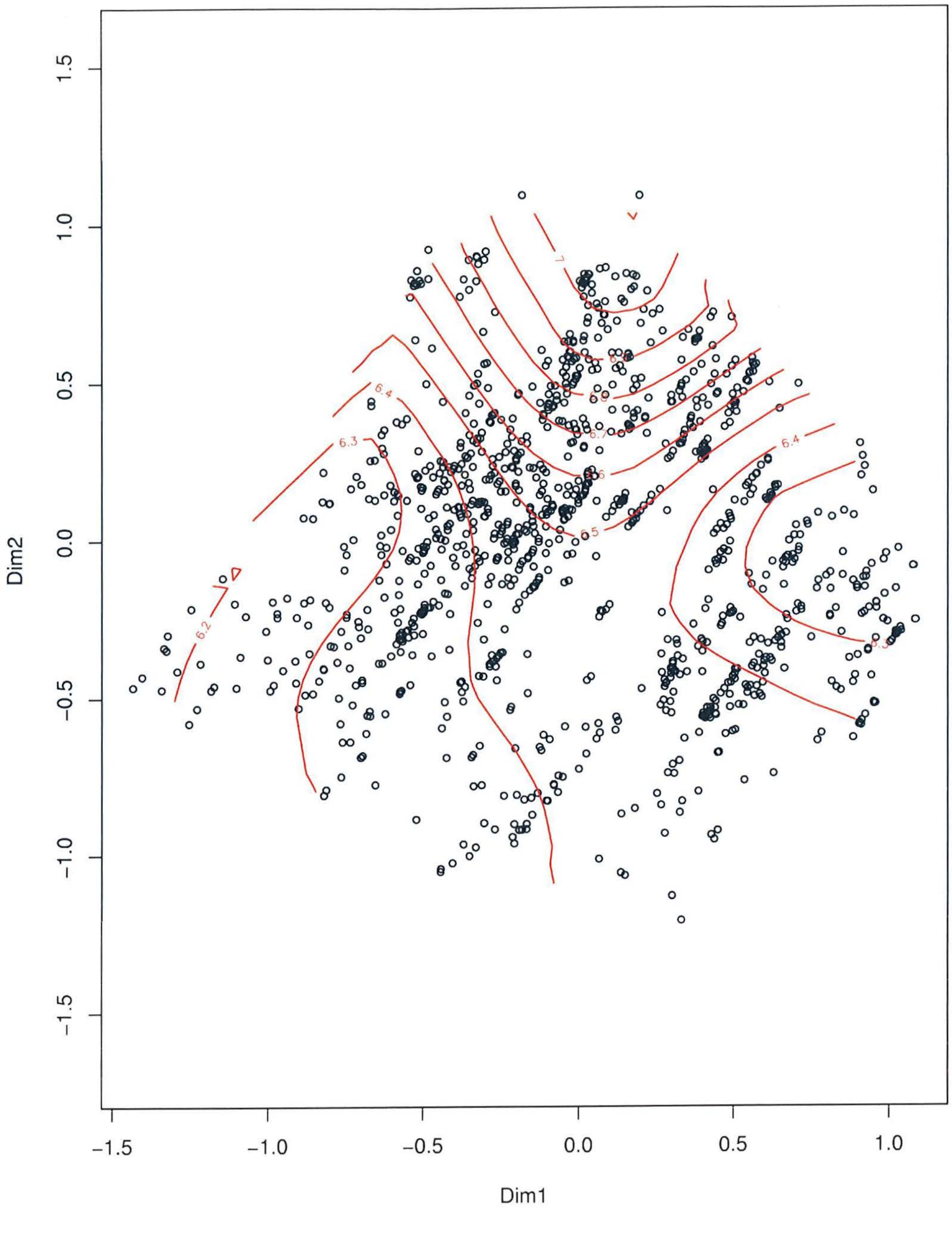

Figure 24

Thinplate spline smoothing contours overlay on ordination plot. Red lines show average radiation during the wettest quarter of the year as described in the methods section of Chapter 4.

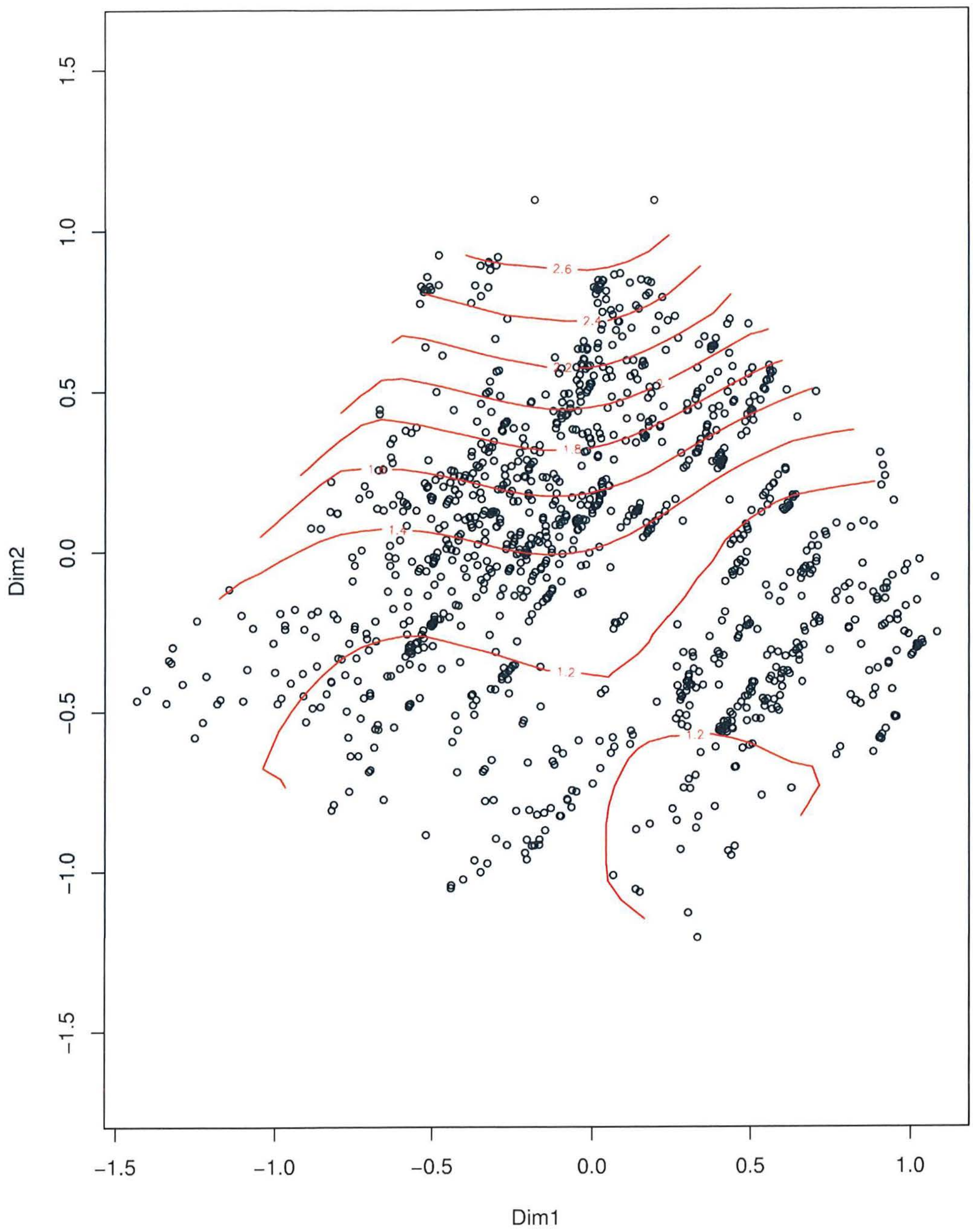

Figure 25

Thinplate spline smoothing contours overlay on ordination plot. Red lines show geology classes as described in the methods section of Chapter 4.

Appendix 9

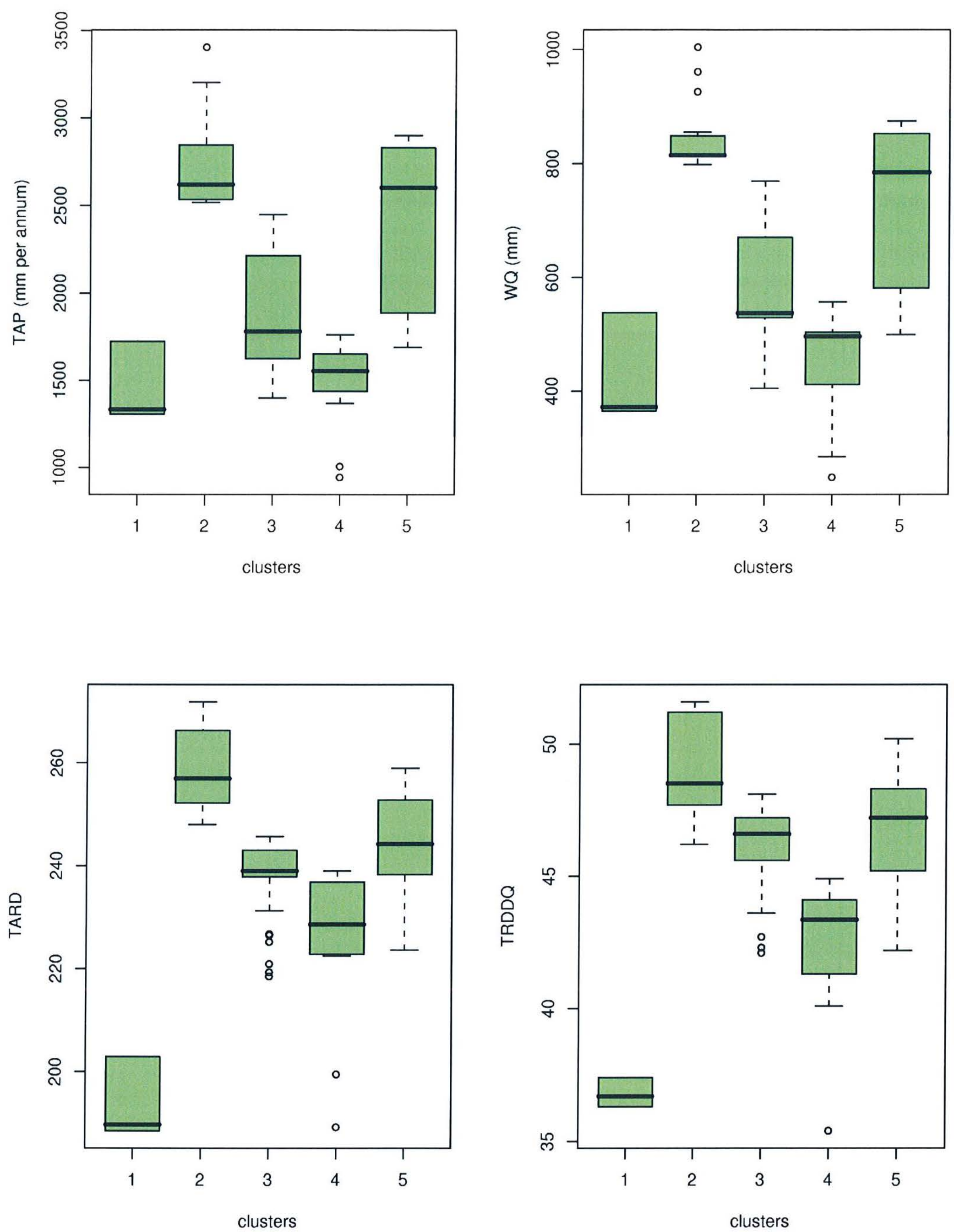

Figure 1

Boxplots showing from right to left; climate clusters and (TAP) total annual precipitation in mm/a, climate clusters and (WQ) total precipitation during the wettest quarter of the year in mm, climate clusters and (TARD) total annual rain days and climate clusters and (TRDDQ) total rain days during the driest quarter of the year.

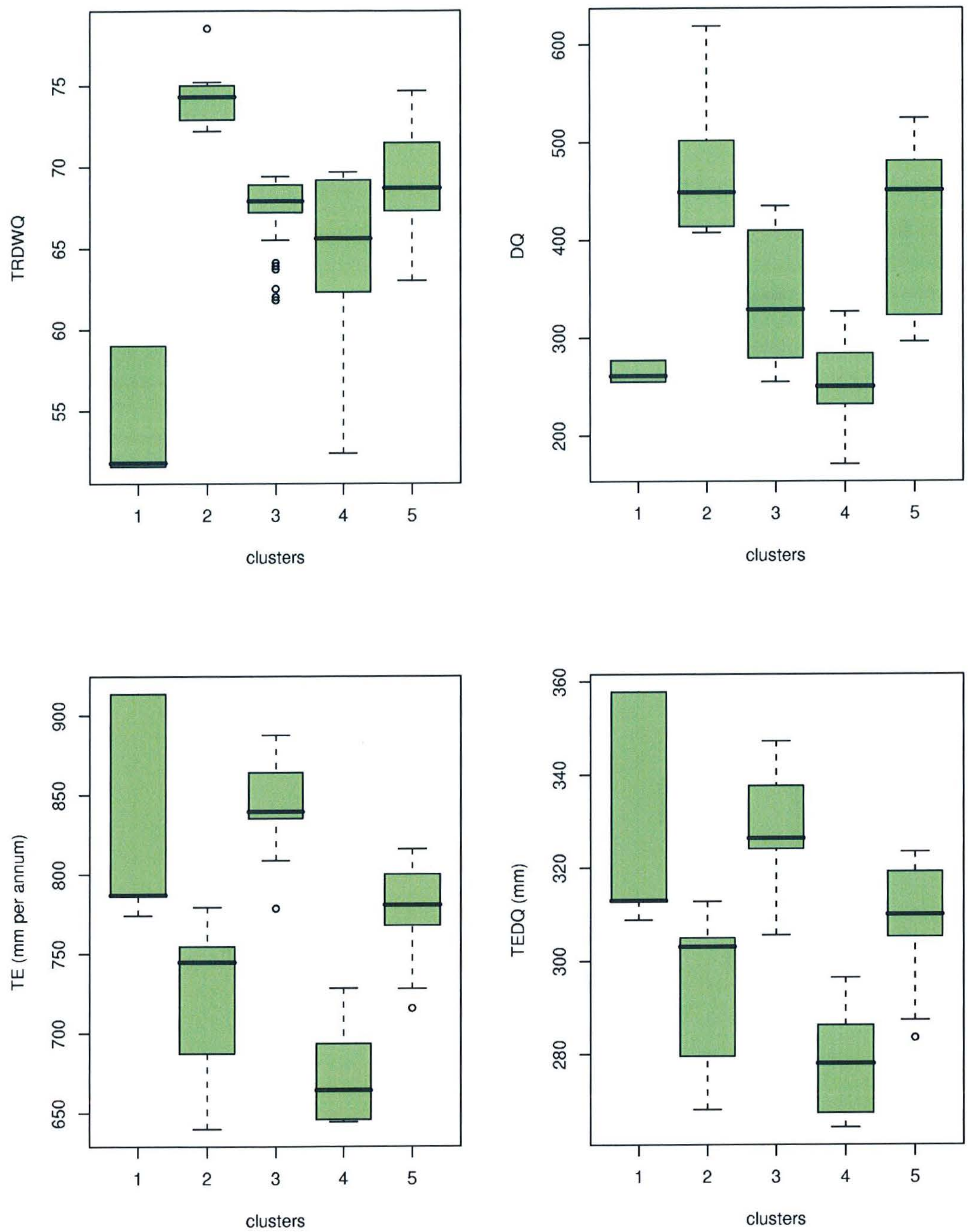

Figure 2

Boxplots showing from right to left; climate clusters and (TRDWQ) total rain days during the wettest quarter of the year, climate clusters and (DQ) total precipitation during the driest quarter of the year in mm, climate clusters and (TE) total annual evaporation in mm/a and climate clusters and (TEDQ) total evaporation during the driest quarter of the year.

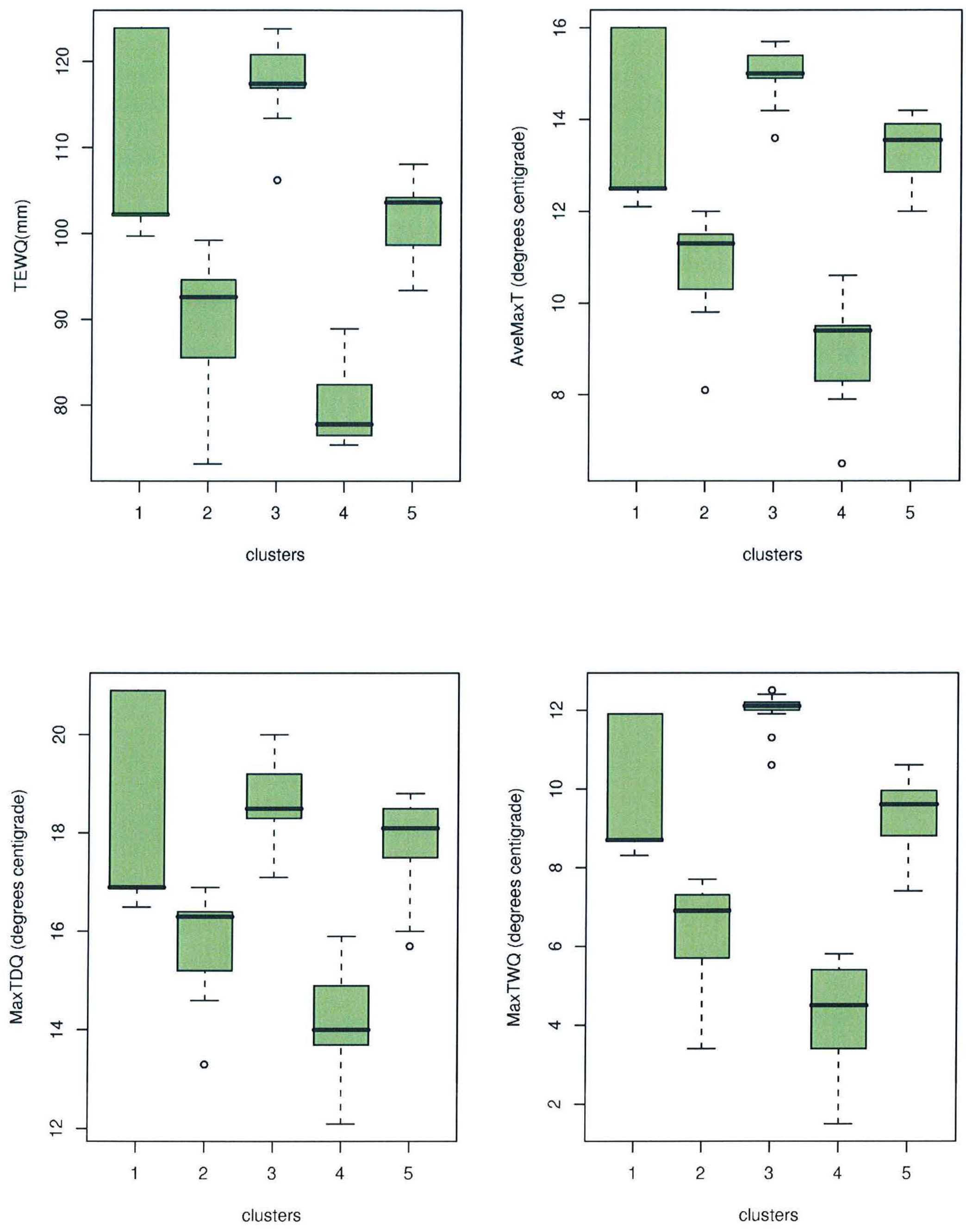

Figure 3

Boxplots showing from right to left; climate clusters and(TEWQ) total annual evaporation during the wettest quarter of the year in mm, climate clusters and (AveMaxT) average maximum temperature, climate clusters and (MaxTDQ) maximum temperature during the driest quarter of the year, climate clusters and (MaxTWQ) maximum temperature during the wettest quarter of the year.

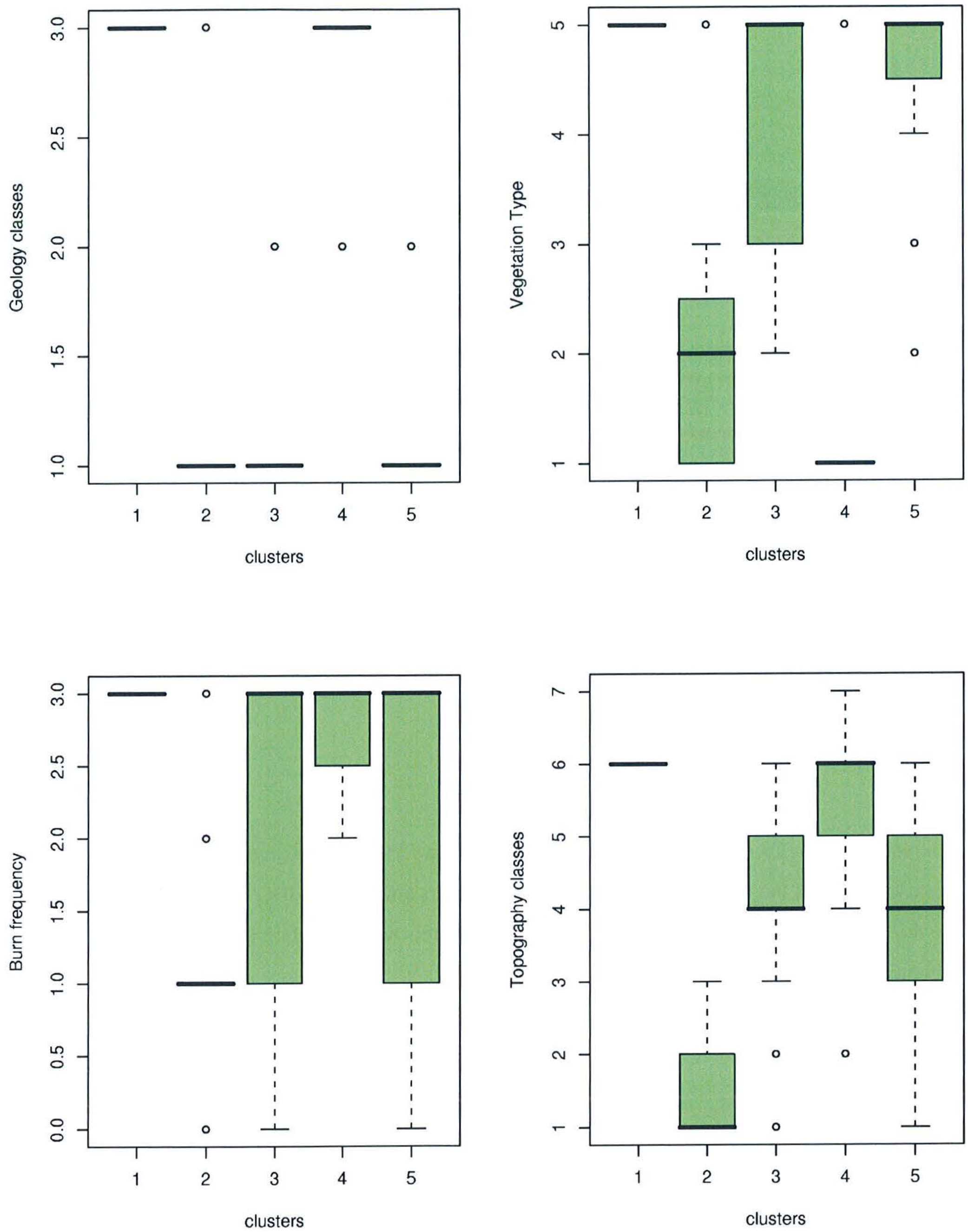

Figure 4

Boxplots showing from right to left; climate clusters and geology classes, climate clusters vegetation type classes, climate clusters and burn frequency classes and climate clusters and topography classes.

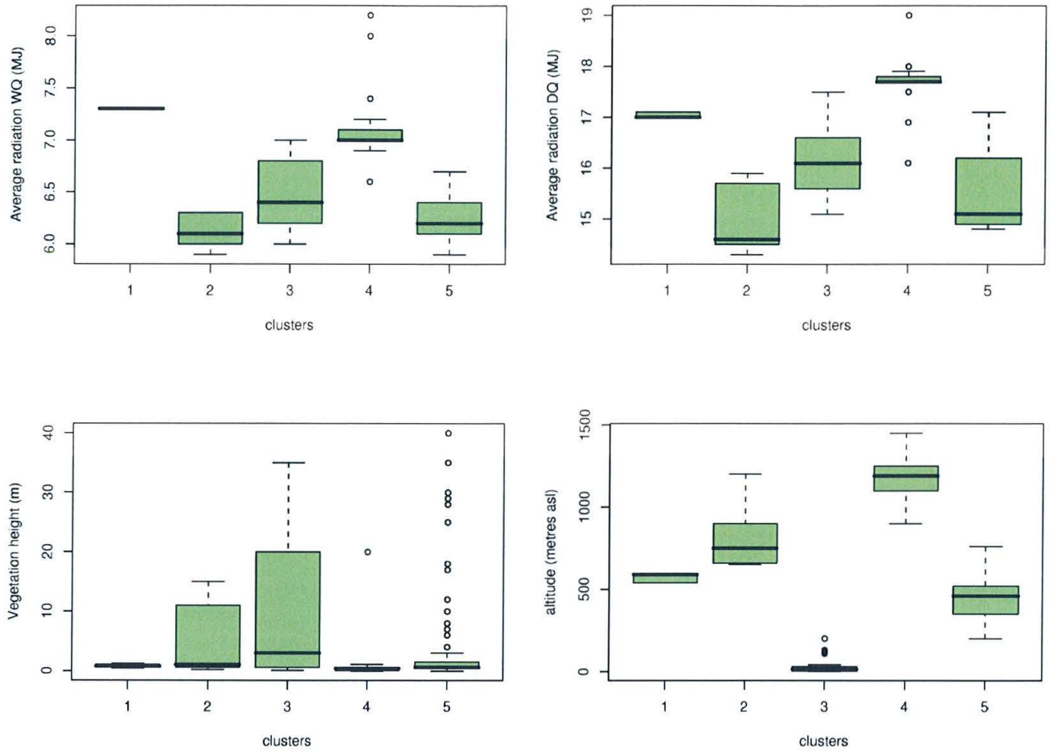

Figure 5

Boxplots showing from right to left; climate clusters and (AveRadWQ) average radiation during the wettest quarter of the year in MJ per m^2, climate clusters and (AveRadDQ) average radiation during the driest quarter of the year in MJ per m^2, climate clusters and vegetation height in metres and climate clusters and altitude in metres above sea level.

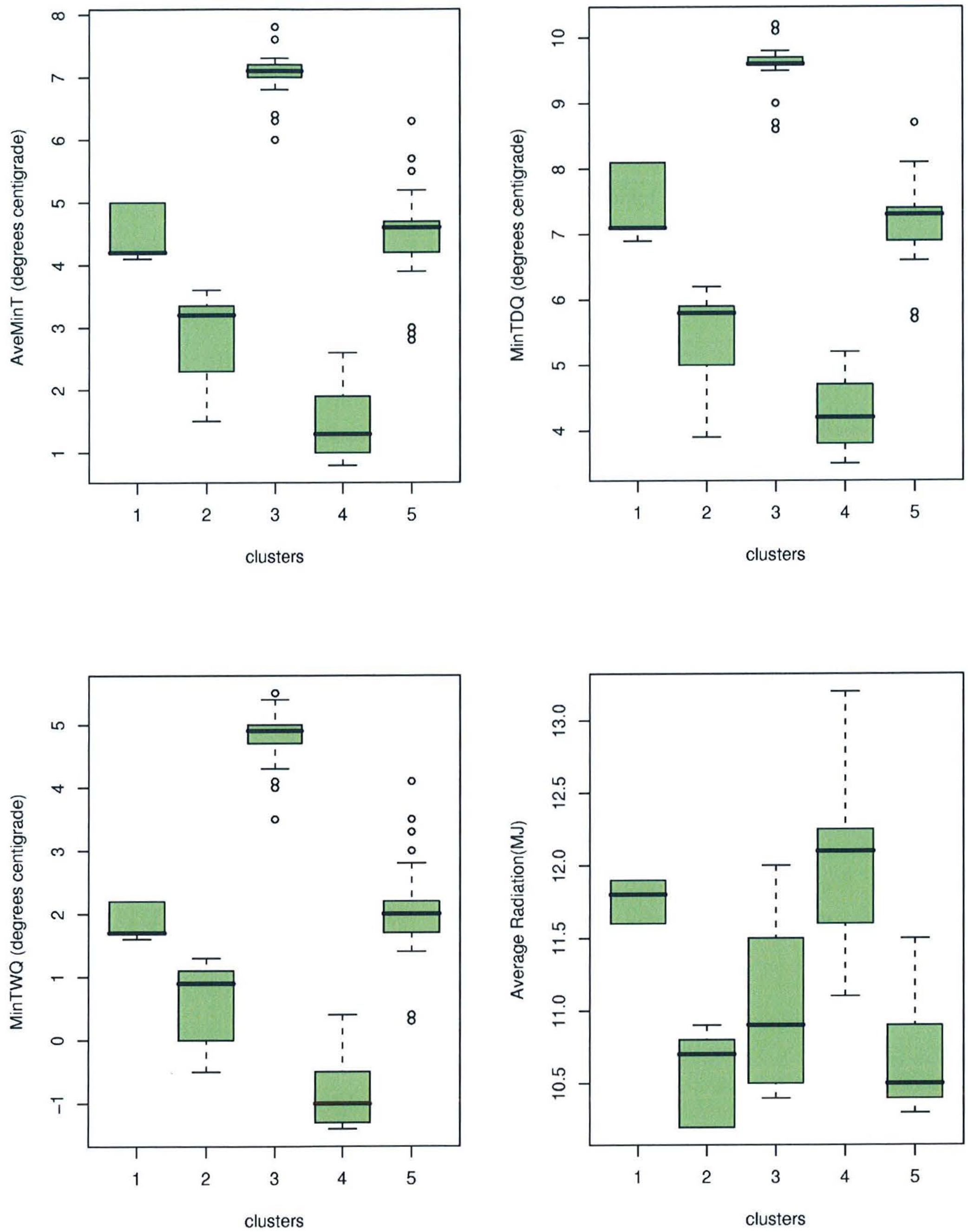

Figure 6

Boxplots showing from right to left; climate clusters and (AveMinT) average minimum temperature, climate clusters and (MinTDQ) minimum temperature during the driest quarter of the year, climate clusters and (MinTWQ) minimum temperature during the wettest quarter of the year and climate clusters and average annual radiation in MJ per m^2.

Appendix 10

Table 1

Soil and environmental variable averages for each climate cluster group. The variable codes are explained in full in Appendices 1 and 6.

		VegType	*Topo*	*Cover*	*Height*	*Geo*	*Alt*	*Burn*	*TAP*	*DQ*
Cluster 1	max	5.0	6.0	100	1.2	3.0	590	3.0	1333	261
	min	5.0	6.0	100	0.5	3.0	540	3.0	1306	255
	mean	**5.0**	**6.0**	**100**	**0.8**	**3.0**	**561**	**3.0**	**1318**	**258**
Cluster 2	max	5.0	3.0	100	15.0	3.0	1200	3.0	3404	619
	min	1.0	1.0	5	0.2	1.0	650	0.0	2517	408
	mean	**2.9**	**1.6**	**96**	**4.9**	**1.2**	**808**	**1.4**	**2854**	**494**
Cluster 3	max	5.0	6.0	100	35.0	2.0	200	3.0	2449	435
	min	2.0	1.0	15	0.1	1.0	3	0.0	1400	255
	mean	**4.0**	**4.1**	**95**	**10.4**	**1.1**	**27**	**2.0**	**1778**	**325**
Cluster 4	max	5.0	7.0	100	20.0	3.0	1450	3.0	1760	327
	min	1.0	2.0	0	0.0	2.0	900	2.0	943	171
	mean	**1.4**	**5.6**	**99**	**1.4**	**2.9**	**1160**	**2.8**	**1490**	**249**
Cluster 5	max	5.0	6.0	100	40.0	2.0	200	3.0	2900	525
	min	2.0	1.0	25	0.0	1.0	750	0.0	1689	296
	mean	**4.6**	**4.0**	**97**	**3.6**	**1.1**	**454**	**2.6**	**2390**	**420**

		WQ	*TARD*	*TRDDQ*	*TE*	*TEDQ*	*TEWQ*	*AvMinT*	*MinTDQ*
Cluster 1	max	372	189.8	36.7	787	313	102	4.2	7.1
	min	365	188.6	36.3	774	309	100	4.1	6.9
	mean	**368**	**189.1**	**36.5**	**782**	**311**	**101**	**4.2**	**7.0**
Cluster 2	max	1004	271.9	51.6	779	313	99	3.6	6.2
	min	798	248.0	46.2	640	268	73	1.5	3.9
	mean	**874**	**260.1**	**49.3**	**726**	**295**	**90**	**3.0**	**5.5**
Cluster 3	max	769	245.7	48.1	888	347	124	7.8	10.2
	min	405	218.5	42.1	779	306	106	6.0	8.6
	mean	**543**	**235.8**	**45.7**	**844**	**328**	**118**	**7.0**	**9.6**
Cluster 4	max	557	239.0	44.9	728	296	89	2.6	5.2
	min	248	189.3	35.4	644	264	75	0.8	3.5
	mean	**461**	**230.4**	**42.8**	**677**	**280**	**79**	**1.3**	**4.0**
Cluster 5	max	874	259.0	50.2	816	323	108	6.3	8.7
	mean	499	223.6	42.2	716	284	93	2.8	5.7
	min	**724**	**243.5**	**46.5**	**779**	**310**	**102**	**4.4**	**7.1**

		MinTWQ	*AvMaxT*	*MaxT DQ*	*MaxT WQ*	*AvRA*	*AvRadDQ*	*AvRaWQ*
Cluster 1	max	1.7	12.5	16.9	8.7	11.9	17.1	7.3
	min	1.6	12.1	16.5	8.3	11.8	17.0	7.3
	mean	**1.7**	**12.3**	**16.7**	**8.5**	**11.9**	**17.1**	**7.3**
Cluster 2	max	1.3	12.0	16.9	7.7	10.9	15.9	6.3
	min	-0.5	8.1	13.3	3.4	10.2	14.3	5.9
	mean	**0.7**	**10.8**	**15.8**	**6.5**	**10.5**	**15.1**	**6.2**
Cluster 3	max	5.5	15.7	20.0	12.5	12.0	17.5	7.0
	min	3.5	13.6	17.1	10.6	10.4	15.1	6.0
	mean	**4.7**	**15.0**	**18.5**	**12.1**	**11.1**	**16.2**	**6.5**
Cluster 4	max	0.4	10.6	15.9	5.8	13.2	19.0	8.2
	min	-1.4	6.5	12.1	1.5	11.1	16.1	6.6
	mean	**-1.0**	**8.9**	**14.2**	**4.1**	**12.1**	**17.7**	**7.1**
Cluster 5	max	4.1	14.2	18.8	10.6	11.5	16.9	6.6
	mean	0.3	12.0	15.7	7.4	10.3	14.8	5.9
	min	**2.0**	**13.2**	**17.9**	**9.3**	**10.7**	**15.5**	**6.2**

Appendix 11

Climatic cluster 1 has a relatively low rainfall of around 1300 mm per annum at an altitude of around 590 m above sea level for areas in the south of Tasmania. In these areas, organosol-producing soil is confined to small patches up to 0.3 km^2 that are topographically controlled. Waterlogged areas on Snug Tiers are an example.

Climatic cluster 2 falls within the wettest part of the state with an average annual rainfall of over 2,500 mm. This cluster represents highland areas in the west and south west of Tasmania at altitudes over 650 m above sea level. Examples of this climatic region are at Mount Murchison, Lake Margaret, Dove Lake and Mount Sprent.

Climatic cluster 3 is predominantly coastal and confined to the west and south west of Tasmania at altitudes below 200 m above sea level and where rainfall is above 1,400 mm per annum. This region experiences the warmest temperatures and the highest evaporation rates of the 5 cluster groups. Examples of this group include Melaleuca, Louisa Plains, Strahan, Cox's Bight and Purrar Point.

Climatic cluster 4 covers the central and eastern upland areas of Tasmania over 900 m above sea level with a rainfall average of over 940 mm per annum. The low temperatures throughout the year, with an average daily minimum temperature of around 0.8°C to an average daily maximum temperature of around 8.9°C, allow for organic accumulation in depressions and valleys. Examples of this are in the Walls of Jerusalem in the western Central Plateau, Mount Wellington, Mount Field and Hartz Peak.

Climatic cluster 5 represents the lower-lying areas of the west and south west of Tasmania between 200 and 750 m above sea-level, which experience high rainfall throughout the year of over 1,600 mm. Examples of this group include Edgar Ponds, Port Davey, Vale of Rasselas, Lake Plimsoll, Newton Creek and Gelegnite Creek.

Appendix 12

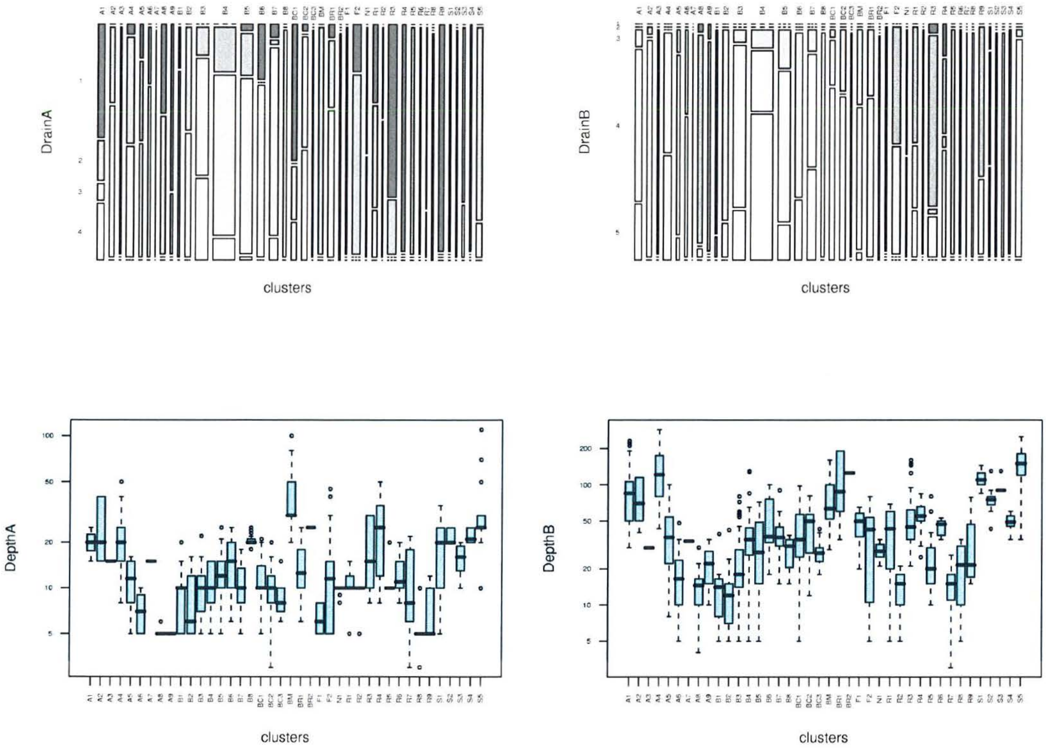

Figure 1

From top to bottom, right to left, mosaic plot with correspondence of supervised clusters with drainage class of the upper horizon (Drain A), drainage class of the lower horizons (Drain B), boxplots of the depth, in centimetres, of the upper horizons (Depth A) and the lower horizons (Depth B). The boxplots have their y axes on a logarithmic scale). The units of measurement and variable codes are given in Appendix 1, cluster codes are explained in Chapter 5 Results section.

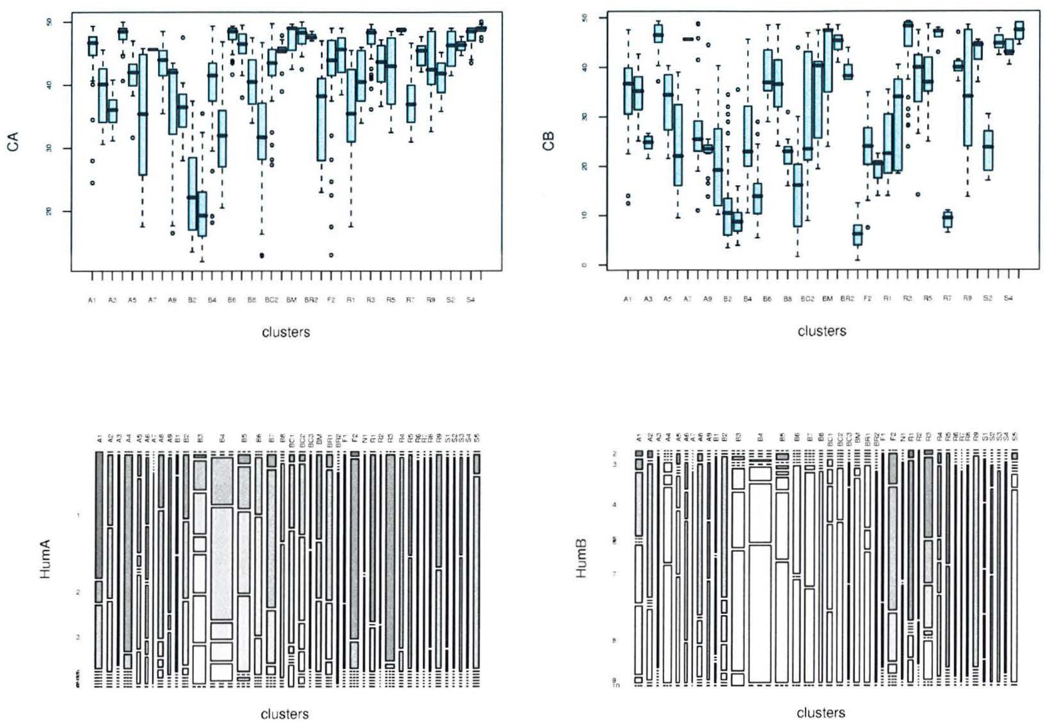

Figure 2

From top to bottom, right to left, boxplots of the organic carbon content in percent of the upper horizons (CA) and the lower horizons (CB), mosaic plots with correspondence of supervised clusters with humification class of the upper horizon (Hum A), humification of the lower horizons (Hum B). The units of measurement and variable codes are given in Appendix 1, cluster codes are explained in Chapter 5 Results section.

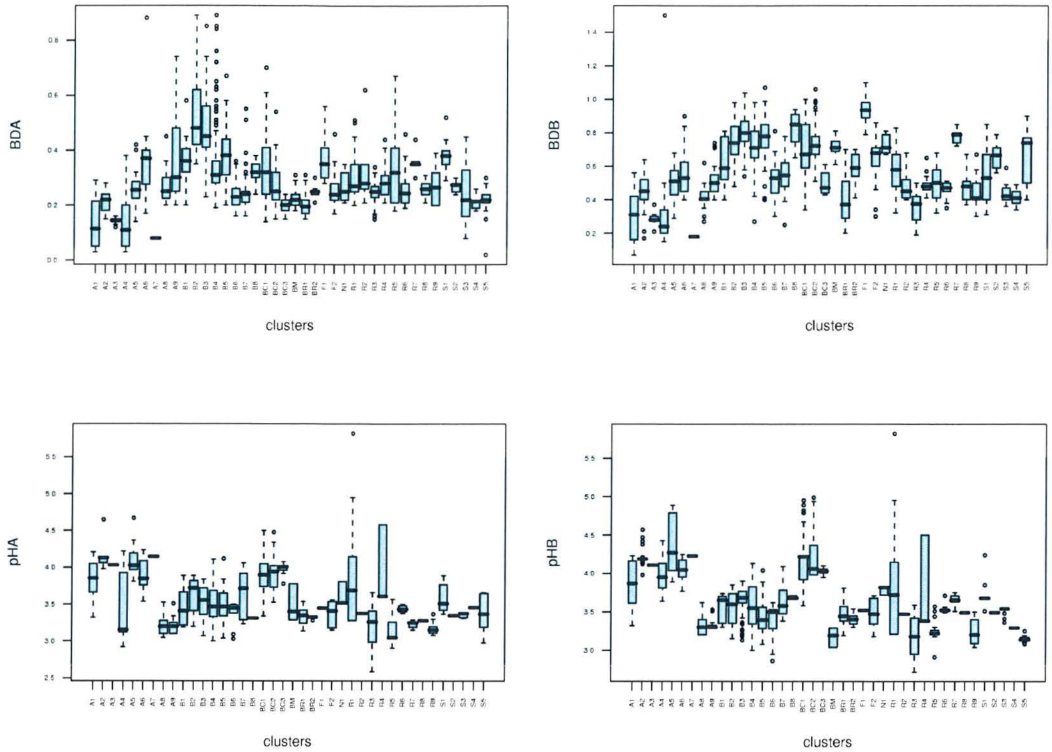

Figure 3

From top to bottom, right to left, boxplots of the bulk density of the upper horizons (BDA) and the lower horizons (BDB), pH of the upper horizons (pH A) and pH of the lower horizons (pH B).). The units of measurement and variable codes are given in Appendix 1, cluster codes are explained in Chapter 5 Results section.

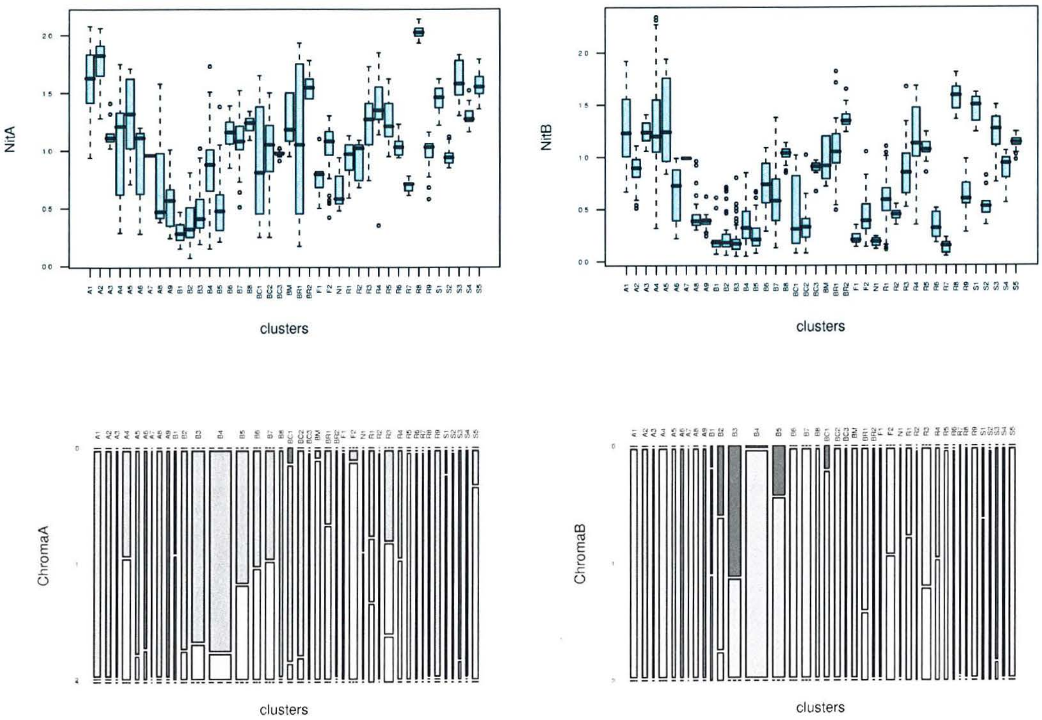

Figure 4

From top to bottom, right to left, boxplots of the organic nitrogen content in percent of the upper horizons (Nit A) and the lower horizons (Nit B), mosaic plots with correspondence of supervised clusters with soil chroma class of the upper horizon (Chroma A), chroma of the lower horizons (Chroma B).). The units of measurement and variable codes are given in Appendix 1, cluster codes are explained in Chapter 5 Results section.

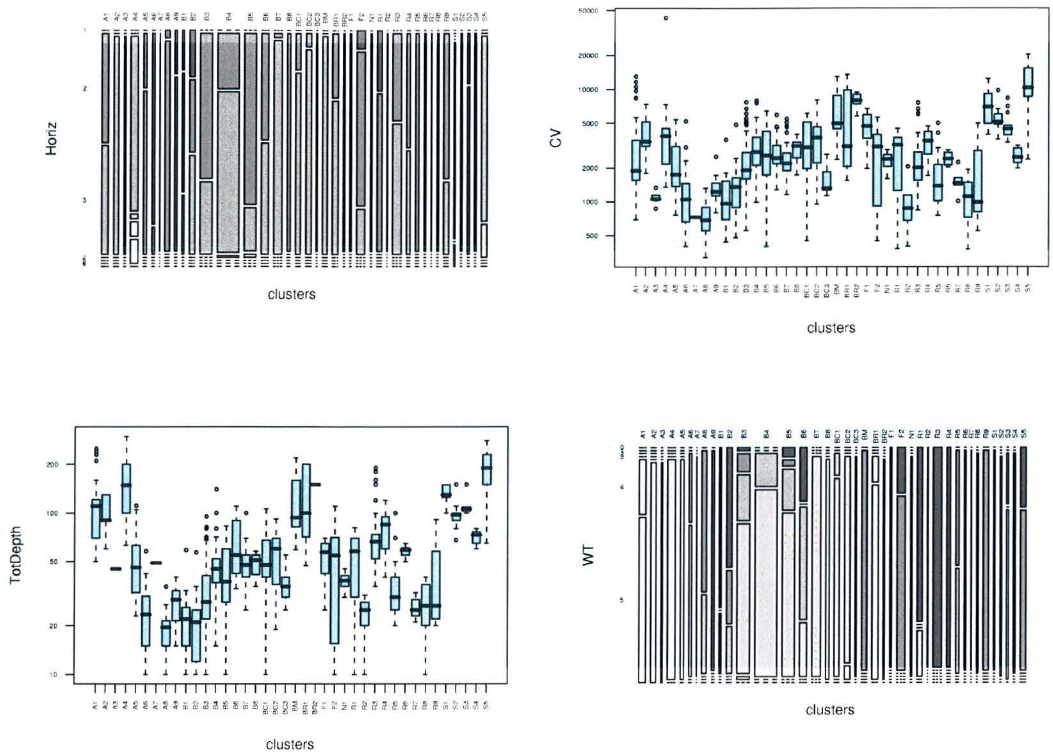

Figure 5

From top to bottom, right to left, mosaic plot of the number of organic horizons in the cluster (Horiz), boxplot of the carbon volume in g/m^2 for the cluster (CV), mosaic plot of the total organic soil depth in cm for each cluster the lower horizons (TotDepth), mosaic plots with correspondence of supervised clusters with water table class of each cluster (WT). The units of measurement and variable codes are given in Appendix 1, cluster codes are explained in Chapter 5 Results section.

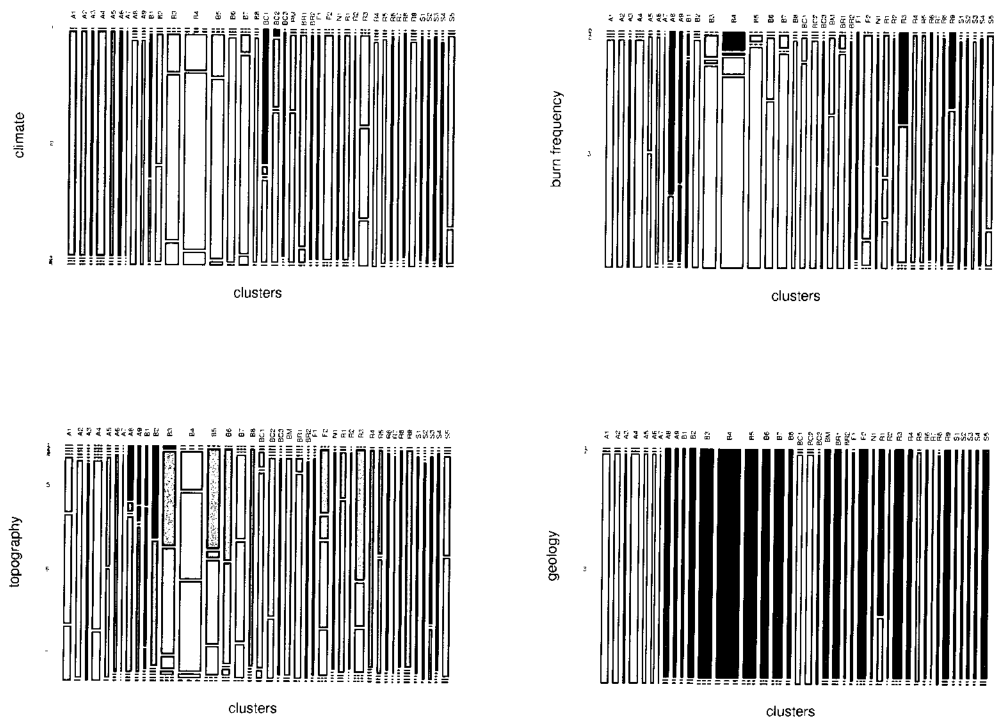

Figure 6

From top to bottom, right to left, mosaic plots with correspondence of supervised clusters with climate class of each cluster group, burn frequency class of each cluster group, topography class of each cluster group and geology class of each cluster group. The class numbering and codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

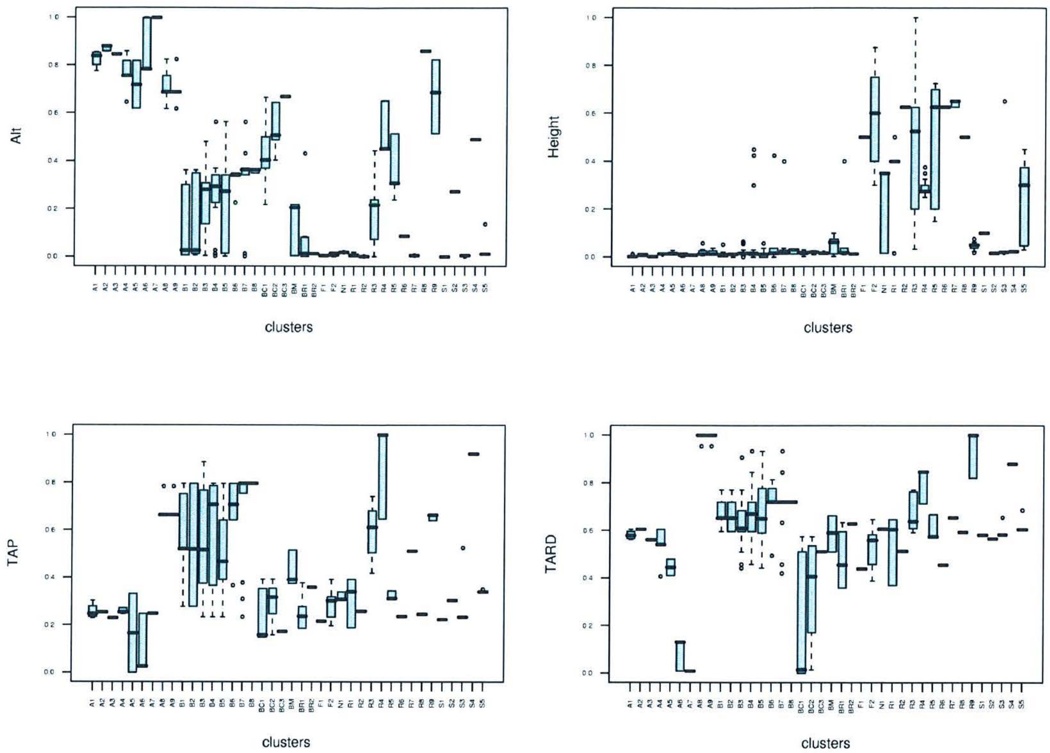

Figure 7

From top to bottom, right to left, boxplots of the altitude (Alt) in metres above sea level, vegetation height (Height) in metres, total annual precipitation (TAP) in mm per annum and total annual rain days (TARD).). The units of measurement and variable codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

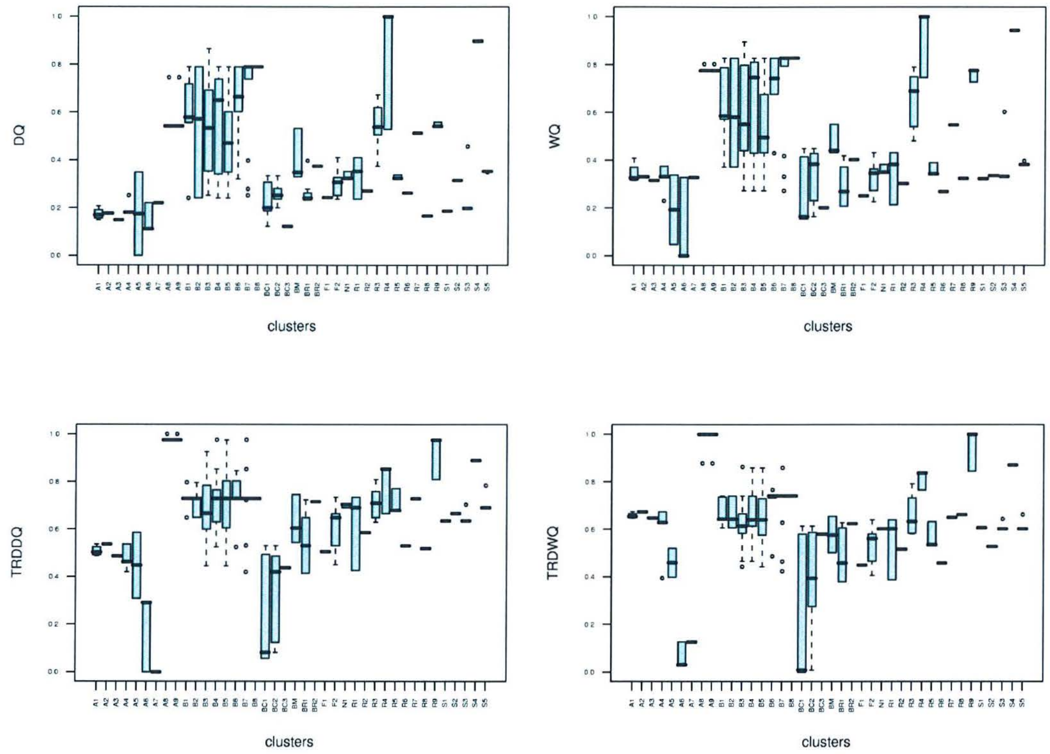

Figure 8

From top to bottom, right to left, boxplots of the total precipitation in the driest quarter of the year in mm (DQ) total precipitation in the wettest quarter of the year in mm (WQ), total number of rain days in the driest quarter (TRDDQ) and total number of days in the wettest quarter (TRDWQ). The units of measurement and variable codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

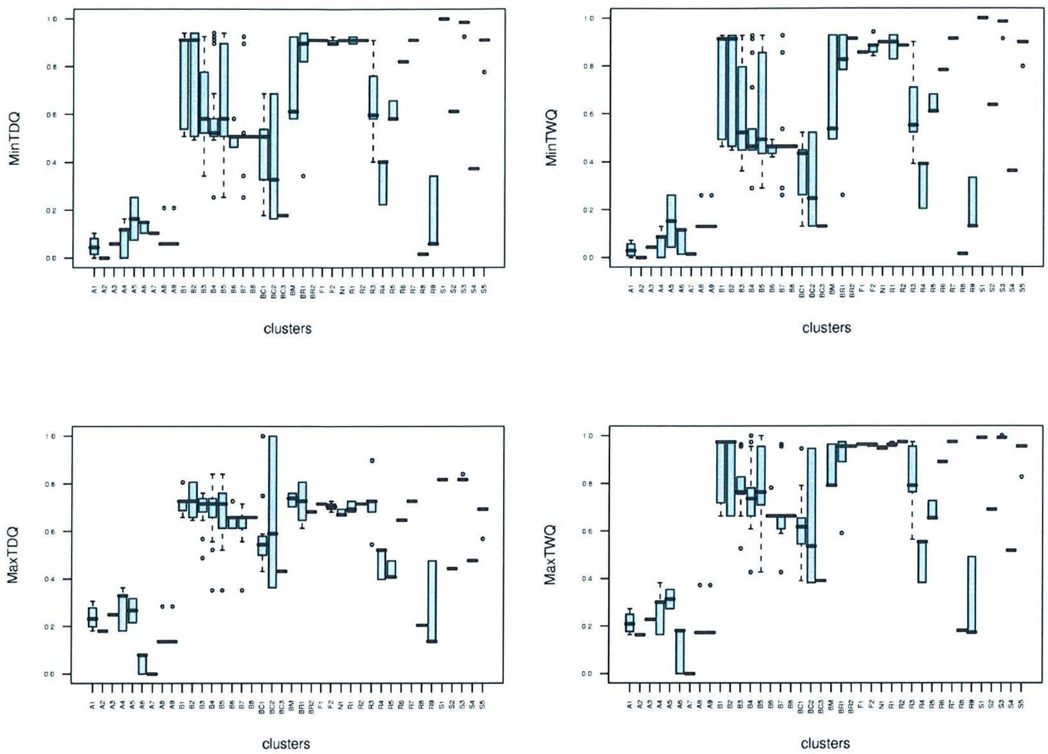

Figure 9

From top to bottom, right to left, boxplots of the minimum temperature during the driest quarter of the year in °C MinTDQ), the minimum temperature during the wettest quarter of the year in °C (MinTWQ), the maximum temperature during the driest quarter of the year in °C (MaxTDQ) and the maximum temperature during the wettest quarter of the year in °C (MaxTWQ). The units of measurement and variable codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

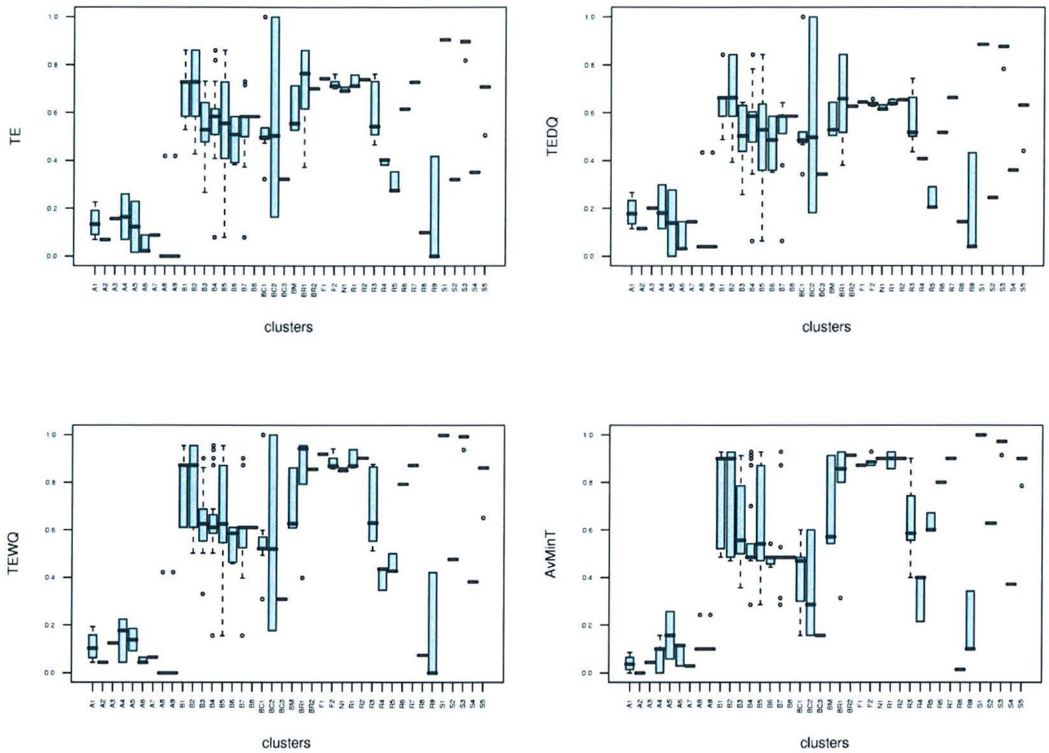

Figure 10

From top to bottom, right to left, total annual evaporation in mm (TE), total evaporation during the driest quarter of the year in mm (TEDQ), total evaporation during the wettest quarter of the year in mm (TEWQ) and average minimum temperature in °C (AvMinT). The units of measurement and variable codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

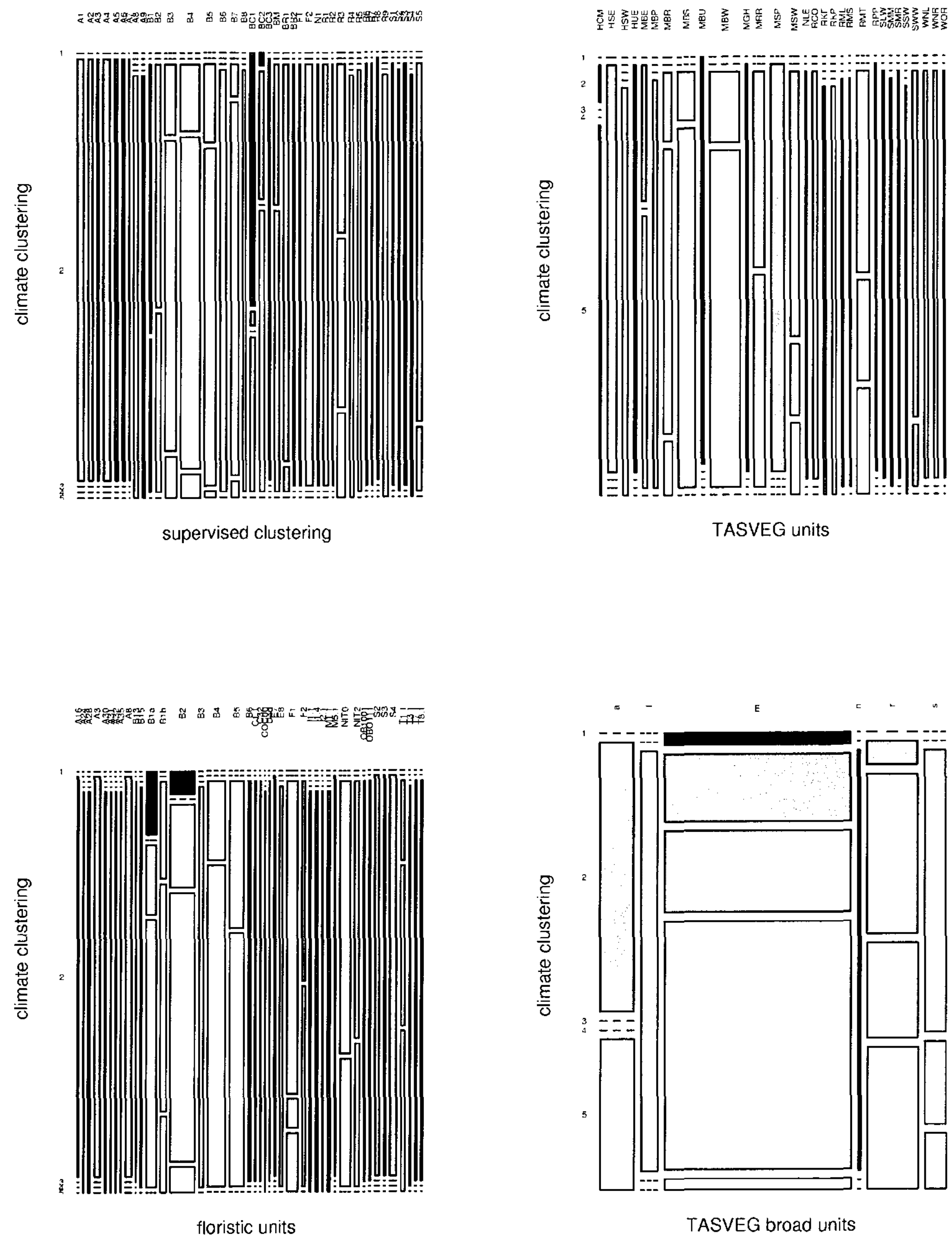

Figure 11

From top to bottom, right to left, mosaic plots with correspondence with climate clusters of the supervised clusters, the TASVEG mapping units, the floristic units and the TASVEG broad vegetation units. The class codes are explained in Chapter 5 Methods and Results section.

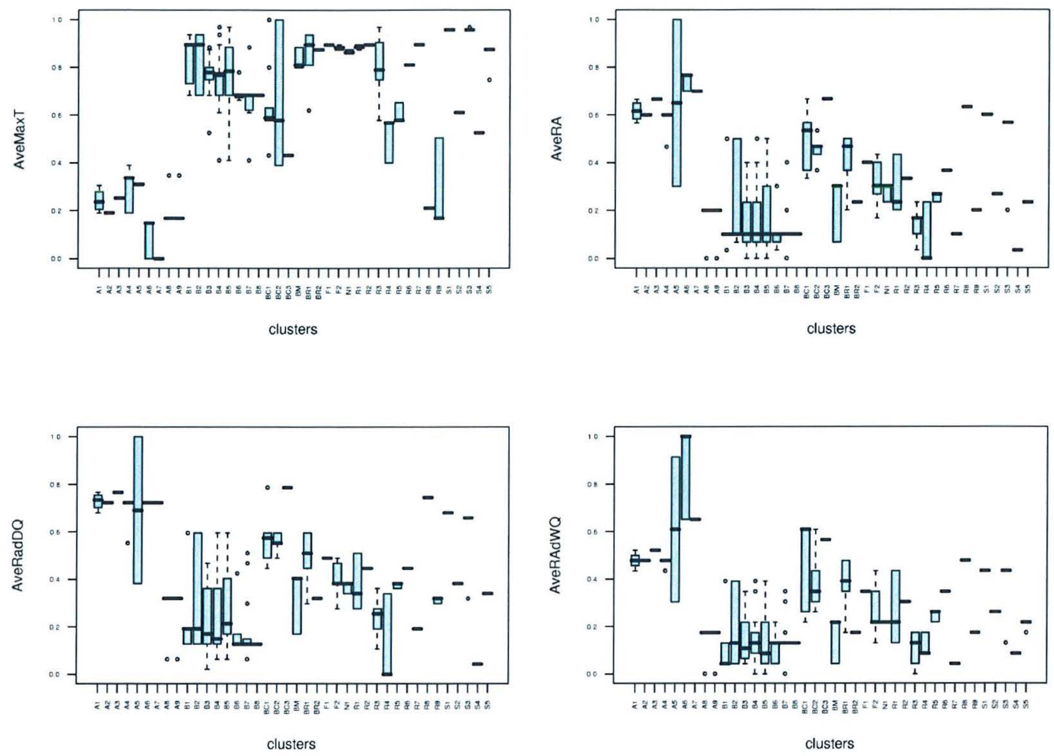

Figure 12

From top to bottom, right to left, boxplots of the average maximum temperature (AveMinT) in °C, average annual radiation (RA) in MW/m^2, average radiation during the driest quarter of the year in (AveRadDQ) and average radiation received during the wettest quarter of the year in MW/m^2 (AveRAdWQ). The units of measurement and variable codes are given in Appendix 6, cluster codes are explained in Chapter 5 Results section.

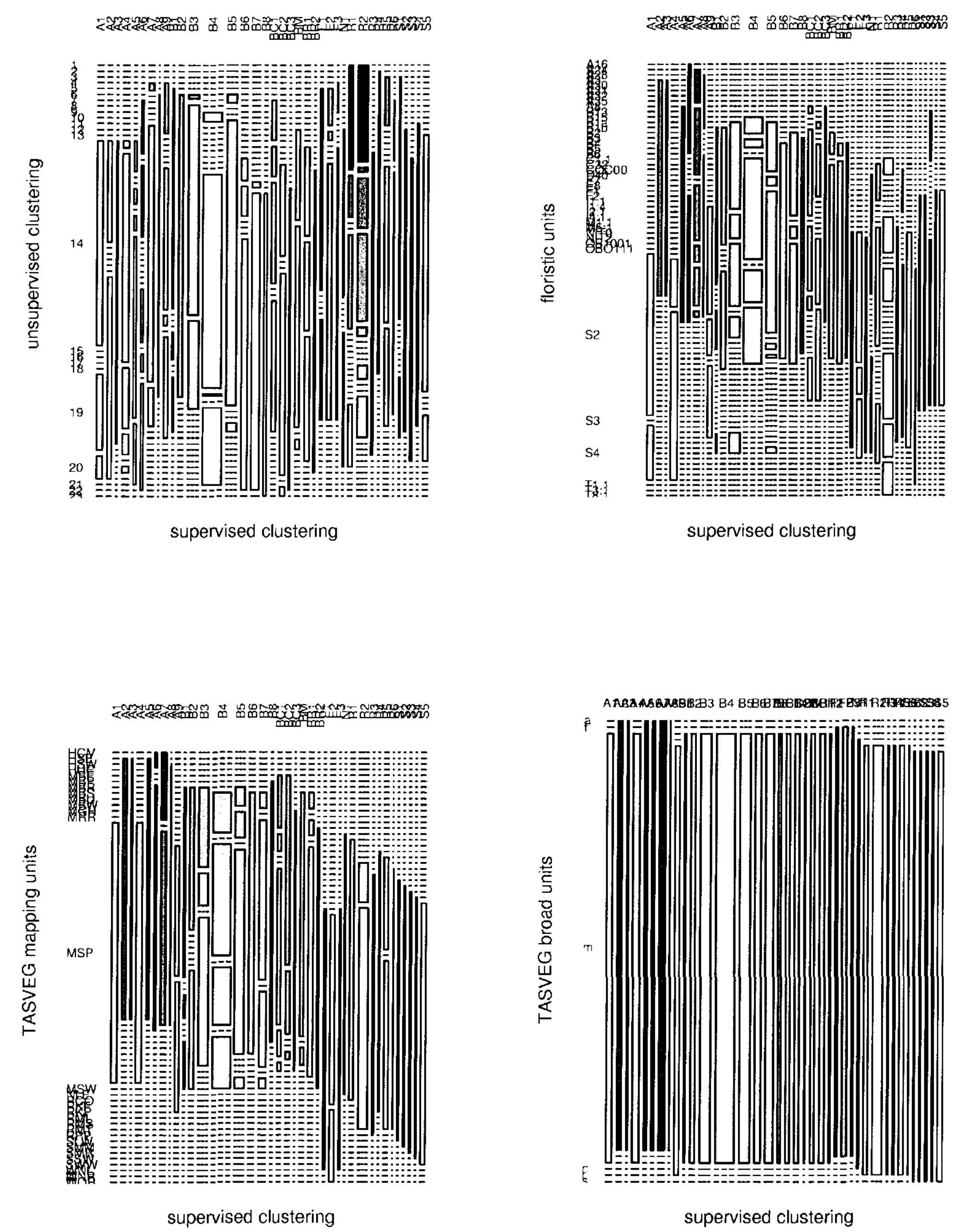

Figure 13

From top to bottom, right to left, mosaic plots with correspondence with supervised clusters of the supervised clusters, the floristic units, the TASVEG mapping units, and the TASVEG broad vegetation units. The class codes are explained in Chapter 5.

Appendix 13

Linear model and generalised additive model outputs

Alpine

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	3.84	0.07	52.19	$< 2 \times 10^{-16}$
slope	-0.06	0.01	-9.96	1.67×10^{-12}

residual standard error 0.21
multiple R^2 0.71
adjusted R^2 0.70
F statistic 99.11
p value 1.67×10^{-12}

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	4.57	4.57	99.11	1.67×10^{-12}
residuals	1.88	0.05		

Alpine – dolerite

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	5.38	0.04	131.93	$< 2 \times 10^{-16}$
slope	-0.36	0.01	-28.28	$< 2 \times 10^{-16}$

residual standard error 0.32
multiple R^2 0.83
adjusted R^2 0.83
F statistic 799.6
p value $< 0.02 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	79.97	79.97	799.61	$< 2.2 \times 10^{-16}$
residuals	16.00	0.10		

GCV – parametric coefficients

	estimate	*standard error*	*t value*	*p value*
intercept	4.47	0.02	212.7	$< 2 \times 10^{-16}$

GCV – approximate significance of smooth terms

	edf	*est. rank*	*F value*	*p value*
slope	3.30	9	133.4	$< 2 \times 10^{-16}$

adjusted R^2 0.88
GCV score 0.07
scale est. 0.07

ANOVA

	Res. DF	*RSS*	*DF*	*SSq*	*F value*	*p value*
log(CV) ~ slope	160.00	16.00				
log(CV) ~ s(slope)	157.70	11.27	2.30	4.73	28.84	$< 1.68 \times 10^{-12}$

Moorland – coastal

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	5.36	0.06	85.26	$< 2.2 \times 10^{-16}$
slope	-0.17	0.01	-22.93	$< 2.2 \times 10^{-16}$

residual standard error 0.47
multiple R^2 0.82
adjusted R^2 0.82
F statistic 526
p value $< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	114.69	114.69	525.91	$< 2.2 \times 10^{-16}$
residuals	25.08	0.22		

GCV – parametric coefficients

	estimate	*standard error*	*t value*	*p value*
intercept	4.31	0.02	191.8	$< 2 \times 10^{-16}$

GCV – approximate significance of smooth terms

	edf	*est. rank*	*F value*	*p value*
slope	6.52	9	250.7	$< 2 \times 10^{-16}$

adjusted R^2 0.95
GCV score 0.06
scale est. 0.06

ANOVA

	Res. DF	*RSS*	*DF*	*SSq*	*F value*	*p value*
log(CV) ~ slope	115.00	25.07				
log(CV) ~ s(slope)	109.47	6.47	5.52	18.61	57.01	$< 2 \times 10^{-16}$

Moorland

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	4.51	0.02	202.53	$< 2.2 \times 10^{-16}$
slope	-0.11	0.00	-40.23	$< 2.2 \times 10^{-16}$

residual standard error 0.27
multiple R^2 0.84
adjusted R^2 0.84
F statistic 1618
p value $< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	125.17	125.17	1618.2	$< 2.2 \times 10^{-16}$
residuals	23.13	0.08		

GCV – parametric coefficients

	estimate	*standard error*	*t value*	*p value*
intercept	3.89	0.01	422.7	$< 2 \times 10^{-16}$

GCV – approximate significance of smooth terms

	edf	*est. rank*	*F value*	*p value*
slope	6.83	9	615.8	$< 2 \times 10^{-16}$

adjusted R^2 0.95
GCV score 0.03
scale est. 0.03

ANOVA

	Res. DF	*RSS*	*DF*	*SSq*	*F value*	*p value*
log(CV) ~ slope	299	23.13			615.8	
log(CV) ~ s(slope)	293	7.45	5.83	15.67	105.72	$< 2 \times 10^{-16}$

Moorland – dolerite

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	5.77	0.09	67.44	$< 2.2 \times 10^{-16}$
Slope	-0.71	0.03	-20.97	$< 2.2 \times 10^{-16}$

residual standard error 0.26
multiple R^2 0.86
adjusted R^2 0.86
F statistic 439.7
p value $< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	29.50	29.50	439.72	$< 2.2 \times 10^{-16}$
residuals	4.70	0.07		

Scrub

response log carbon kg C m^2
predictors $slope^3$

	estimate	*standard error*	*t value*	*p value*
intercept	5.60	0.05	100.5	$< 2.2 \times 10^{-16}$
$slope^3$	-1.45×10^{-3}	7.03×10^{-5}	-20.65	$< 2.2 \times 10^{-16}$

residual standard error 0.34
multiple R^2 0.82
adjusted R^2 0.82
F statistic 426.4
p value $< 2.2 \times 10^{-16}$

ANOVA

$slope^3$	47.93	47.93	426.38	$< 2.2 \times 10^{-16}$
residuals	10.23	0.11		

Wet eucalypt forest

Response	log carbon kg C m^2
predictors	slope, AvMinT

	estimate	*standard error*	*t value*	*p value*
intercept	3.7	0.42	-8.79	6.36×10^{-12}
slope	-0.1	0.01	-9.61	3.29×10^{-13}
AvMinT	0.27	0.06	4.41	5.02×10^{-05}

residual standard error	0.37
multiple R^2	0.73
adjusted R^2	0.72
F statistic	71.49
p value	8.90×10^{-16}

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	17.12	17.12	123.5	1.85×10^{-15}
AvMinT	2.7	2.7	19.48	5.02×10^{-05}
residuals	7.35	0.13		

Response	log carbon kg C m^2
predictors	slope

	estimate	*standard error*	*t value*	*p value*
intercept	5.51	0.11	48.37	$< 2 \times 10^{-16}$
slope	-0.11	0.01	-9.59	$< 2.92 \times 10^{-13}$

residual standard error	0.43
multiple R^2	0.63
adjusted R^2	0.62
F statistic	92.01
p value	$< 2.93 \times 10^{-13}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	17.12	17.12	92.01	2.93×10^{-13}
residuals	10.05	0.19		

Montane rainforest

Response	log carbon kg C m^2
predictors	AveMaxT

	estimate	*standard error*	*t value*	*p value*
intercept	-4.56	0.59	-7.73	5.75×10^{-10}
AveMaxT	0.59	0.04	14.48	$< 2 \times 10^{-16}$

residual standard error	0.36
multiple R^2	0.81
adjusted R^2	0.81
F statistic	209.5
p value	$< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
MaxTDQ	26.54	26.54	209.53	$< 2.2 \times 10^{-16}$
residuals	6.08	0.13		

Coastal rainforest

Response	log carbon kg C m^2
predictors	Slope

	estimate	*standard error*	*t value*	*p value*
intercept	6.21	0.28	21.84	$< 2 \times 10^{-16}$
Slope	-0.33	0.04	-8.46	4.53×10^{-9}

residual standard error	0.48
multiple R^2	0.73
adjusted R^2	0.72
F statistic	71.5
p value	4.53×10^{-9}

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
Slope	16.81	16.81	71.54	4.53×10^{-9}
residuals	6.34	0.23		

Coastal rainforest

response	log carbon kg C m^2
predictors	AveMinT

	estimate	*standard error*	*t value*	*p value*
intercept	-24.53	2.75	-8.94	1.50×10^{-9}
AvMinT	4.03	3.39	10.37	6.47×10^{-11}

residual standard error	0.42
multiple R^2	0.80
adjusted R^2	0.79
F statistic	107.5
p value	6.48×10^{-11}

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
AvMinT	18.51	18.51	107.54	6.48×10^{-11}
residuals	4.65	0.17		

Coastal rainforest

Response log carbon kg C m^2
predictors TARD

	estimate	*standard error*	*t value*	*p value*
intercept	-14.61	1.93	-7.56	3.94×10^{-8}
TARD	0.08	0.01	9.60	3.39×10^{-10}

residual standard error 0.44
multiple R^2 0.77
adjusted R^2 0.77
F statistic 92.15
p value 3.39×10^{-10}

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
TARD	17.91	17.91	92.15	3.39×10^{-10}
residuals	5.25	0.19		

Rainforest

Response log carbon kg C m^2
predictors slope, vegetation height and TARD

	estimate	*standard error*	*t value*	*p value*
intercept	9.54	2.51	3.79	3.17×10^{-4}
slope	0.21	0.02	12.28	$< 2.2 \times 10^{-16}$
height	0.03	0.01	3.92	2.09×10^{-4}
TARD	-0.03	0.01	-3.25	1.81×10^{-3}

residual standard error 0.36
multiple R^2 0.85
adjusted R^2 0.84
F statistic 127.4
p value $< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	44.93	44.93	352.82	$< 2.2 \times 10^{-16}$
height	2.40	2.40	18.84	4.91×10^{-5}
TARD	1.34	1.34	10.56	1.81×10^{-3}
residuals	8.53	0.13		

Response log carbon kg C m^2
predictors slope

	estimate	*standard error*	*t value*	*p value*
intercept	3.48	0.1	34.8	$< 2.2 \times 10^{-16}$
slope	0.08	0.01	12.08	$< 2.2 \times 10^{-16}$

residual standard error 0.35
multiple R^2 0.69
adjusted R^2 0.69
F statistic 144.5
p value $< 2.2 \times 10^{-16}$

ANOVA

	sum of squares	*mean of squares*	*F value*	*p value*
slope	17.16	17.16	144.46	$< 2.2 \times 10^{-16}$
residuals	7.6	0.12		

Appendix 14

Table 1

Environmental factor range for broad vegetation groups described in Chapter 6.

	Alt	*TAP*	*DQ*	*WQ*	*TARD*	*TRDDQ*	*TRDWQ*	*TE*	*TEDQ*	*TEWQ*	*AveMinT*	*MinTDQ*	*MinTWQ*	*AveMaxT*
Alp1	900-1200	2570-2875	410-505	830-855	268-272	51-52	75-79	640-755	268-305	73-95	1.5-2.5	3.9-4.9	-0.5-0.4	8.1-9.8
Alp3	900-1450	940-1760	170-330	245-560	189-239	35-45	52-70	644-711	264-292	75-85	0.8-2.6	3.5-5.2	-1.4-0.4	6.5-10.2
MontRf	750-1250	1540-2580	245-420	495-830	238-272	44-51	69-79	640-755	268-305	73-95	0.9-3.2	3.6-5.8	-1.3-0.9	8.1-11.3
Rf	0-700	1580-3400	290-620	470-1000	231-259	45-49	66-74	750-849	303-334	95-119	3.6-7.1	6.2-9.6	1.3-4.9	11.9-15.7
Coastal Rf	0-30	1400-1900	270-360	400-575	219-243	42-47	62-69	834-848	324-326	117-121	6.8-7.3	9.5-9.7	4.3-5	14.8-15
WetFor	30-750	1520-1800	280-330	450-545	227-244	44-48	64-69	716-834	284-324	95-117	5-7.1	7.4-9.6	2.8-4.8	12-14.8
CoastForest	0-20	1400-1910	275-340	400-575	219-243	42-47	62-69	835-848	324-326	117-121	6.8-7.3	9.5-9.7	4.3-5.1	14.9-15
Scrub	0-750	1490-3200	250-575	490-960	236-262	46-50	66-75	728-888	287-347	93-124	3.4-7.8	6-10.2	1.1-5.5	11.5-15.7
Moor	20-820	1500-3100	280-560	450-930	224-266	42-51	63-75	662-840	270-324	81-119	2.8-6.9	5.2-9.5	0.4-4.5	10.4-14.9
Moor3	540-980	1300-1910	226-320	365-588	189-237	36-44	52-68	685-914	281-358	82-124	1.9-5	4.6-8.1	-0.5-2.2	10.2-16
coastalmoor	0-20	1400-2250	276-435	400-700	218-244	42-48	62-69	809-876	313-343	113-122	6.4-7.3	9-9.8	4-5	14.2-15.7

	MaxTDQ	*MaxTWQ*	*AveRA*	*AveRadDQ*	*AveRadWQ*	*CV range*	*CV average*
Alp1	13.3-14.6	3.4-5.6	10.2-10.8	14.6-15.8	5.9-6.3	12-76	26
Alp3	12.1-15.3	1.5-5.7	11.1-13.2	16.1-19	6.6-8.2	6-427	112
MontRf	13.3-16.3	3.4-6.9	10.8-12.1	15.7-17.8	6.3-7	16-237	72
Rf	16.7-20	7.6-12.2	10.2-11.2	14.3-16.4	5.9-6.6	7-370	102
Coastal Rf	18.1-18.5	12-12.2	10.8-11.5	15.6-16.7	6.2-6.9	9-145	71
WetFor	15.7-18.3	8.7-12	10.9-11.3	15.9-16.4	6.4-6.7	6-908	185
CoastForest	18.1-18.5	12-12.1	10.7-11.5	15.6-16.7	6.2-6.9	9-190	60
Scrub	16-19.5	7.2-12.5	10.3-12	14.5-17.5	6-6.9	7-556	140
Moor	15.2-18.8	6.2-12	10.2-11.4	14.4-16.7	5.9-6.7	7-204	60
Moor3	15.3-20.9	5.7-11.9	11.3-12.2	16.6-18	6.5-7.3	11-261	120
coastalmoor	17.8-19.5	11.3-12.5	10.4-11.7	15.1-17.1	6-7	9-569	132

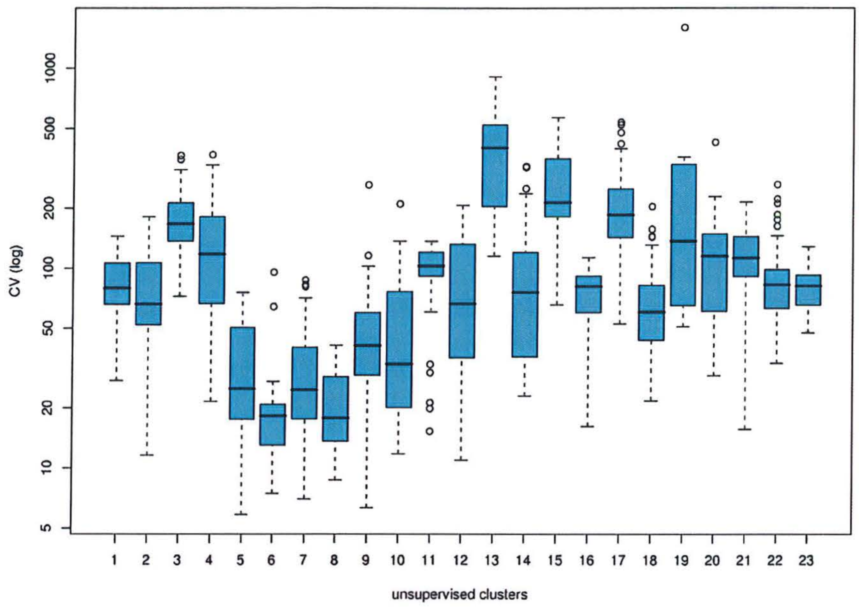

Figure 1

Soil organic carbon stocks in organosols classified in terms of unsupervised clusters produced in Chapter 4. Soil organic carbon in log kg C m^2.

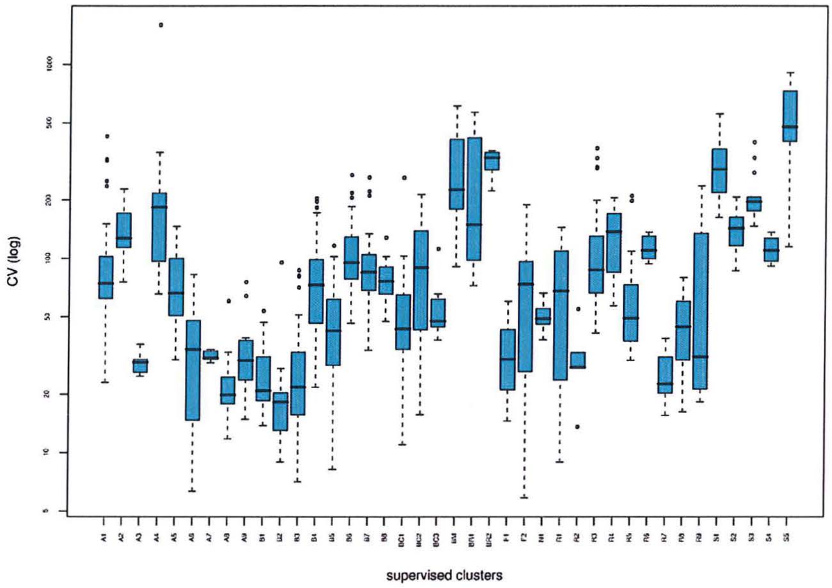

Figure 2

Soil organic carbon stocks in organosols classified in terms of supervised clusters produced in Chapter 5. Soil organic carbon in log kg C m^2.

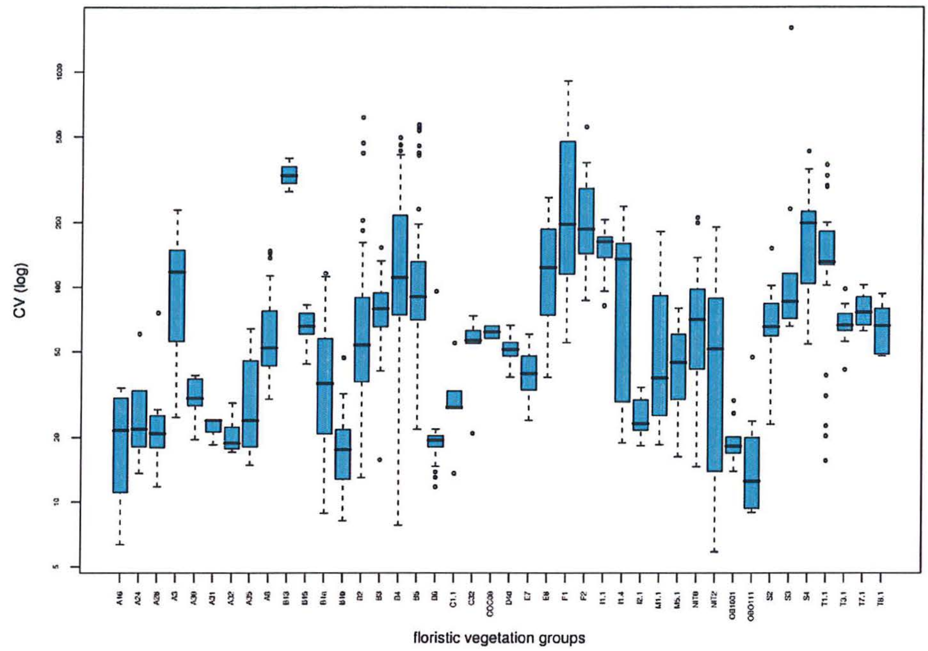

Figure 3

Soil organic carbon stocks in organosols classified in terms of floristic vegetation units described in Chapter 5. Soil organic carbon in log kg C m^2.

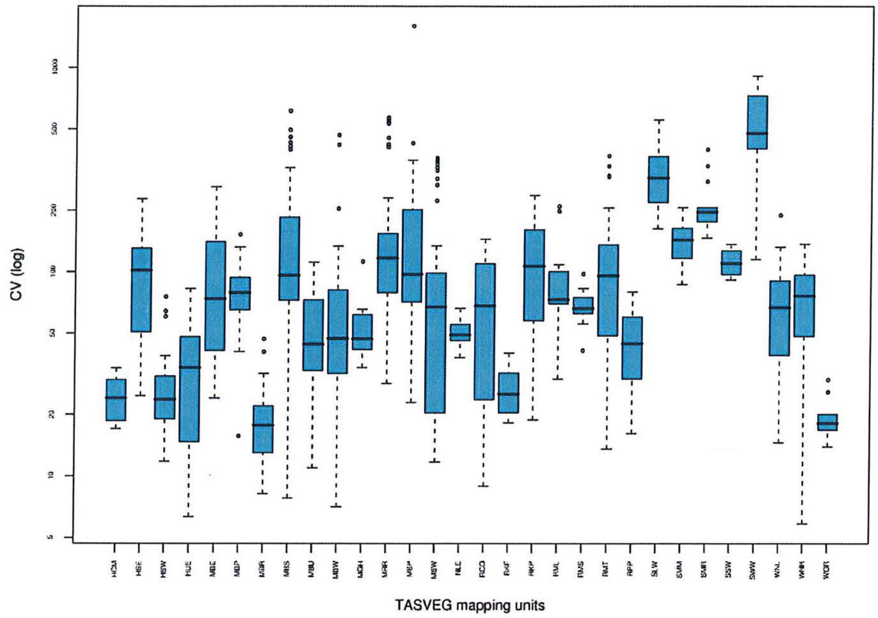

Figure 4

Soil organic carbon stocks in organosols classified in terms of TASVEG vegetation mapping units described in Chapter 5. Soil organic carbon in log kg C m^{2}.